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RELIABILITY ASSESSMENT OF ROAD RESTRAINT SYSTEMS

Hodnocení spolehlivosti silničních zádržných systémů

Doctoral thesis

Ing. Michal Kalinský

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A thesis has been worked out in the doctoral degree study programme at the Department of Structural Reliability, Klokner Institute, Czech Technical University in Prague.

Applicant:	Michal Kalinský
Doctoral Degree Study Programme:	Civil Engineering
Branch of Study:	Theory of Structures
Supervisor:	doc. Ing. Jana Marková Ph.D. Department of Structural Reliability Klokner Institute Czech Technical University in Prague Šolínova 6 166 08 Prague 6

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Anotace

Předkládaná disertační práce je zaměřena na využití simulací metodou konečných prvků při posouzení odolnosti a spolehlivosti silničních zádržných systémů, se zaměřením na ocelová svodidla při zatížení nárazem těžkých vozidel. Téma zohledňuje několikaleté zkušenosti autora ze simulací zkoušek svodidel předních evropských výrobců, prováděné v TÜV SÜD Czech s.r.o

V práci je kromě klasických analytických přístupů, založených na normativních podkladech a energetických přístupech, představena metodika analýzy nárazových testů pomocí nelineárních dynamických simulací. Tento postup je následně validován na několika případových studiích vybraných z databáze výsledků nárazových zkoušek silničních svodidel. Databáze byla sestavena za podpory akreditované zkušebny ve Spolkové republice Německo a je součástí výsledků práce.

V úvodu je definován mezní stav únosnosti pro silniční svodidla a podobné konstrukce, který nebyl doposud přesně popsán. Pro analytické modely se jedná o základní hodnotící parametr. Další část je již věnována pokročilým postupům modelování nárazového děje pomocí nelineárních dynamických simulací. Dále se zabývá stanovením a kvantifikací modelových nejistot vztahujících se k nárazovým zkouškám.

Simulační přístupy, které jsou popsány a verifikovány v první části, jsou využity pro nový přístup pravděpodobnostního hodnocení svodidel zatížených nárazem vozidel v běžném provozu.

V závěru práce jsou použité metody a modely aplikovány na problematiku stanovení nárazové síly od těžkých vozidel do podpěrných konstrukcí mostů. Odhad nárazové síly se stanoví zejména pro podpěrné konstrukce chráněné silničními svodidly.

Klíčová slova

Silniční svodidla, nárazová zkouška, pravděpodobnost, spolehlivost, numerické simulace, crash test

Abstract

The dissertation focuses on the use of finite element analysis in the durability and reliability assessment of road restraint systems, with a focus on steel barriers subjected by heavy vehicle impact loading. The topic reflects authors several years of experience in simulating impact tests of road barriers for leading European manufacturers, carried out at TÜV SÜD Czech Ltd.

In addition to classical analytical approaches based on normative bases and energy approaches, the thesis develops a methodology for the analysis of impact tests using nonlinear dynamic simulations. This approach is then validated on several case studies selected from the Road barrier impact test results database. The database has been developed for the purpose of this work with the support of accredited testing laboratory in Germany as an integral part of the results.

The work defines the ultimate limit state for road barriers and similar structures, which has not been accurately described yet. For analytical models this represent a basic evaluation parameter. Furthermore, the thesis deals with explanation of the crash event modelling using nonlinear dynamic simulations. Next section is devoted to a determination and analysis of the model uncertainties in relation to crash tests. The effect of the selected model uncertainties on the test results is then quantified with the aid of simulations.

The simulation approaches described and verified in the first part are further used to propose a probabilistic assessment of road barrier subjected to heavy traffic impact.

Finally, the methods and models used in this thesis are applied to solve the task of determining the impact force from heavy vehicles on bridge support structures, mainly those protected by road barriers.

Keywords

Road barriers, crash test, impact, probability, reliability, numerical simulation

Table of content

Symbols and abbreviations

Abbreviations

ASI	Impact Severity Index
CAE	Computer Aided Engineering
CDF	Cumulative Distribution Function
CEN	Comité Européen de Normalisation
CoG	Centre of Gravity
EuroNCAP	The European New Car Assessment Programme
FE	Finite Element
FEA	Finite Element Analysis
HGV	Heavy Goods Vehicle
JCSS	Joint Committee on Structural Safety
LGV	Large Goods Vehicle
LHS	Latin Hypercube Sampling
NDP	National Determined Parameters
NLDFEA	Non-Linear Dynamic Finite Element Analysis
RRS	Road Restraint Systems
SAE	Society of Automotive Engineers
THIV	Theoretical Head Impact Velocity
TKP	Technical Quality Conditions
TP	Technical Conditions
ULS	Ultimate Limit State
VCDI	Vehicle Cockpit Deformation Index
VI	Vehicle Intrusion
W	Working width

Symbols

Latin upper-case letters

D or D_{dyn}	Dynamic deflection
E	Load effect
F_d	Design force
$F(x)$	Cumulative distribution function of a random variable X
$G(\boldsymbol{X})$	Limit state function
P	Probability
P_{f}	Probability of failure
X	Vector of random variables

Latin lower-case letters

$f(x)$	Probability density function of a random variable X
m	Mass
k	Stiffness

Greek upper-case letters

Φ	Standardized normal cumulative distribution function
Θ_E	Model uncertainties for load effect
Θ_R	Model uncertainties for structural resistance

Greek lower-case letters

α	Sensitivity coefficient
β	Reliability index
β_t	Reference (target) reliability index

Foreword

The accident rate on roads in the Czech Republic, as well as in other European countries, still represents serious problem. The number of fatalities, or seriously injured people, is high, in spite of the producers' efforts to make cars safer, and both governmental and non-governmental organizations' attempts to educate drivers. Despite the tend to suspend the drivers from the driving the human factor seems to be the most critical part of the transportation proces.

For idea, social losses in terms of the financial costs arising from traffic accidents were estimated in 2018 at 80,1 billion CZK. This figure represents 1,5% of the gross domestic product for the year 2018.

From actual traffic accident statistics, it is obvious that:

- Crash with the obstacle represents 20,5% of all accidents, with average number of 5,2 killed people per 1000 accidents
- Crash with the rigid obstacles leads to more severe consequences
    - Crash with the trees, with average number of 28,5 killed people per 1000 accidents
    - Crash with the rigid wall (tunnels, bridges…), with average number of 5,3 killed people per 1000 accidents
    - Crash with the road barrier represents one of the minor parts (12,2%) of all crashes with the obstacle, with average number of 3 killed people per 1000 accidents.

We can only assume that the number of the killed or injured peoples due to the crash with the rigid obstacle can be significantly lower in any case of safety measures installed in dangerous road area.

There are not so many possibilities to reduce the risks arising from potential accidental situation on the roads. One of the most effective measure is installation of the road restraint system (hereafter RRS) in the dangerous road vicinity [1].
Therefore, the road barrier structures represent relatively popular, simple, and cost-effective measure to minimise possible loses and consequences arising from the accidental impact.

Road barrier testing issues
The road barrier is quite a specific product that differs significantly from other types of structures. It is very difficult to define the parameters for road barriers to be met, as millions of different impact combinations can occur in real operation. On the road is high number of vehicles of different sizes, body shapes, weight, technical condition etc. Such vehicles are moving at different speeds and directions. We should also consider the effect of global conditions, e.g. road condition, weather conditions, the driver human factor, installation of barriers etc. Finally, we get an almost unlimited number of different impact combinations.
Thus, whatever road barrier structure is installed on the road, a much heavier impact than for which the structure was designed and tested can occur.

The current situation in the field of road barriers testing and certification seems to be very complicated. It is a general misunderstanding that the European Union is responsible for road safety in the individual Member States. This responsibility is fully transferred to the national ministries of transportation.
The paradox is that ministries are responsible for road safety and they have to use "approved" road barriers (understand as CE-marked products). They may use other barriers in very limited and justified cases only.
Manufacturers are now trying to offer road barriers at the lowest possible price due to increasing competition and pressure from authorities. Therefore, current manufacturer's trend is to minimize the costs for the physical testing as well as shorten the development time as much as possible.

The result is a product designed close to the mandatory limit with a very low margin for any heavier impact. Nowadays the significant impact to the final quality can be noticed. Some of the RRS are

tested for many times with the same conditions. System can be installed on the roads, if one of these tests is successful. Such test is simply a statistical extreme. It’s obvious, that there is no safety margin over than minimal legislation limits. In case of unfavourable circumstances (like the vulnerable structural system, inappropriate installation and other uncertainties) the system resistance may not pass at least the minimal legislation limit.
Many countries are not satisfied with road barrier quality and with increasing competition cheating. This is one of the main topics to be solved at European committee for Standardization, Technical Body CEN/TC226, Working Group WG1. Some of the member states issues brand with new national requirements. For instance, in Belgium, thanks to their courage in government decision-making, their own RRS assessment requirements are introduced, completely independent from the certification of EN1317. Therefore, they refuse any RRS that does not meet their national requirements. It is based on the premise that the ministry has responsibility for the road safety.

There is a crucial question whether Member State, responsible for a road safety, can refuse the road barrier even though it has CE declaration of conformity? Member States, including the Czech Republic, must face a number of lawsuits from manufacturers to restrict and block access to the market. This issue is now engaged by several experts in the road barrier branch.

Obviously, there are also other issues that should also be addressed. With regards to expert’s statement, up to 10% of road barriers are installed contrary to how they were tested. In these cases, it is an improper installation. The last decade is typical by significant increase in heavy goods traffic. In case of heavy goods vehicle crash most of the road barrier structures are very low effective.

Nobody cares about the procedure on how manufacturers get the CE declaration of conformity. The result is again a very low-strength product that can be installed on the roads. Thus, current habits in new road barriers design should be verified. It is highly advisable to utilize all existing methods and approaches to design reliable and safe products.

Fig. 1: Heavy goods vehicle traffic increasing – illustrative figure

Along with the increase of heavy goods vehicle traffic, there is also an increase in accidents imposed by these vehicles. Among those with most serious consequences are situations where the crashing vehicle overcomes the barrier and continues its movement with a slightly changed trajectory only. In the worst case, the vehicle continues through the centre lane further into the opposite lane with all associated consequences, including life losses.

Very serious are also the accidents, when the vehicle hits an obstacle or a structure in the road vicinity after overcoming the road barrier. Assessment of these serious accidental situations is one of the main features of this work.

1 Thesis aim and motivation

Safety of road restraint systems is frequently discussed topic within the European Community, because the dissatisfaction of states with the quality of road barriers as well as the traffic intensity and composition are continuously growing.

During my practice, I often met with problems of designing new types of road barriers. Thanks to experience in other areas, the potential of using numerical simulations was obvious at first glance. Nevertheless, only a few manufacturers and test laboratories use these approaches. It is primarily due to the very expensive technical background, both in financial terms and human resources. The fact is that numerical simulations (even if they could be very accurate and predictive) cannot fully substitute a physical test for certification of the final product yet.

In the contrary the road barriers are still developing. Their design must respond to new challenges and market demands, e.g. the motorcyclist protection zones or price reduction pressure as well as lifetime durability etc.. Numerical simulations represent one of the few ways how to achieve these goals already in initial development phase and with a high probability to successfully pass the physical test.

Experts also point out that road barriers are becoming less durable, mainly due to competitive pressure on low prices. Unfortunately, products with low reliability margin are entering on the market.

The motivation for this work is to provide a comprehensive insight into the road barrier design and to analyse the potential of numerical simulations in their development. An integral part of the development is the safety performance analysis in accidental design situations and probability assessment of the structure subjected by real impact in ordinary traffic.

This thesis has been written in English to broaden the spectrum of readers.

1.1 Road barrier assessment

Accidental design situation with context of the work is perceived as a physical normative crash test and vehicle impact to the obstacle, protected by road barriers (later in thesis).

The main objective is to improve the theoretical models of the road barriers impact as close as possible to the physical crash tests. To fulfil the main objective of the main research questions, the milestones must be stated, given as:

- Stage 1: Refinement of the ultimate limit state (ULS) definition for road barrier structures. The definition of ULS wasn’t directly considered in the standardised requirements for the road barriers verifications and described yet.
- Stage 2: Propose virtual method of real road barrier crash test that would reflect all features and scenarios of real physical crash tests.
- Stage 3: Calibrate the virtual simulation approach using the real crash test data.
- Stage 4: Specify and improve the theoretical model uncertainties with regards to the physical crash test.
- Stage 5: Analyse the effect of the model for uncertainties on crash test results.
- Stage 6: Propose the probabilistic assessment method to evaluate the safety performance of the road barrier imposed by real impact in ordinary traffic.

Analysis of the road restraint system crash behaviour is based on non-linear dynamic finite element simulations (hereinafter FEA). Modelling approach is validated with the real tests thanks to authors cooperation with the testing laboratory TÜV SÜD GmbH.

1.2 Bridge pier impact force analysis

Partial aim of the work is to apply the virtual modelling approach to analyse the impact forces to supporting structures or obstacles in the dangerous vicinity of the roads imposed by Large Good Vehicles (LGV). Therefore, next milestones are defined.

- Stage 7: Refinement of the existing analytical vehicular impact models. To complete with the road barrier features.
- Stage 8: Implement the numerical simulation methods from previous stages to analyse the impact force to the bridge pier imposed by LGV.
- Stage 9: Analyse the impact force in case of the pure impact to bridge pier (no road barrier protection).
- Stage 10: Analyse the impact force in case of the impact to bridge pier with road barrier protection.

Currently the accidental impact force imposed by LGV, which is considered in design of the structures, seems to be significantly underestimated. Design forces are provided by EN1991-1-7 and ISO 10252 for typical impact scenario and unprotected structures.

Nevertheless the computational simulations and other studies [2] [3] [4] [5] show that typical example of pure accidental impact could lead to significantly higher impact forces. Thus, appropriate safety measures to reduce the impact force, should be considered in design.

Protection of supporting structures by the road barriers is given in EN1991-1-7, the recommended procedures can be nationally refined in the National Annex considering the National Determined Parameters. This practice is in competence of the national ministry of transportation and the National Standardisation Institute (NSB). Obviously, road barriers cannot be capable to reduce the impact forces from the heavy goods vehicles within the limits, due to the reason above. The main reason is to avoid likely fatal contact with the structure and redirect the impacting vehicle, however, to decreasing the impact force to the structure should be also mentioned. Fortunately, today most of the structures in the road vicinity are protected by road barriers.

1.3 Thesis benefits and framework

The main thesis benefit is the proposal of methodology how to validate theoretical approaches for verification of the road barriers, mainly the virtual simulations and minimise the differences between the theoretical and full-scale physical crash test. The statistical data folder is utilized to calibrate the virtual models and simulation procedure.

However, the research effort cannot reflect all possible real-world scenarios of different types of structural systems of the road safety barriers. Therefore, thesis work focus must have some constraints, particularly:

- Steel road barriers only.
  Other types of the road barriers mainly concrete monoblocks are excluded from the work. However, they are mentioned in the theoretical part of the thesis. The concrete road barriers have completely different crash behaviour due to material properties.
- Road barrier installed into the ground or bridge parapet.
  Other types of the installation e.g., temporary barriers or road barrier as integral part of the noise barrier exceeds the scope of the work.

- Heavy good vehicles (HGV) impact.
  Thesis framework is almost fully focused on the impact caused by LGV and HGV e.g., trucks and busses. Impact imposed by the light vehicles e.g., passenger cars are also involved in the work. However, for further analysis it plays commentary role only.
- Unintentional impact
  All crash scenarios considered in the work proceeds from the fundamental presumption of unintentional type of the impact. Impact conditions in the intentional impact are significantly different and exceed the scope of the work.

Thesis is also intended to offer realistic view on the size of the impact forces to bridge substructures or other structures located in the vicinity of roads, which are now almost exclusively protected by road barriers. Also, to answer the key question: How large the impact force can be in vehicle collision with the structure and obstacles (e.g., trees, traffic mark posts, bridge piers etc.) protected by road barriers.

2 State of the art

2.1 Road restraint systems

Roadside safety research started around 50 years ago when traffic grew and when the first highways appeared. The accidents when the vehicle leaves their road are one of the most dangerous due to the likely contact with the rigid obstacles in the road vicinity. There were many fatalities as well as seriously injured peoples. In these "early days", development of structures aiming to restrain an impact vehicle mostly used to be made using common sense, engineering judgement and many crash tests.

Wikipedia quotation "*Traffic barriers keep vehicles within their roadway and prevent them from colliding with dangerous obstacles such as boulders, sign supports, trees, bridge abutments, buildings, walls, and large storm drains, or from traversing steep (non-recoverable) slopes or entering deep water. They are also installed within medians of divided highways to prevent errant vehicles from entering the opposing carriageway of traffic and help to reduce head-on collisions. Some of these barriers, designed to be struck from either side, are called median barriers. Traffic barriers can also be used to protect vulnerable areas like school yards, pedestrian zones, and fuel tanks from errant vehicles.*"

Next functionality of the road barrier as a preventive measure of the road safety should be mentioned. The structures located in the vicinity of highways and roads may be endangered by vehicle impact (light passenger cars, heavy cars, busses, trucks, and truck with the trailers). Therefore, road barriers provide protection for traffic on roads, as well as for their immediate surroundings.

Road barriers are a part of the wide Road restraint systems (RRS) group. The definition and sorting of the RRS is shown in

Fig. 2.

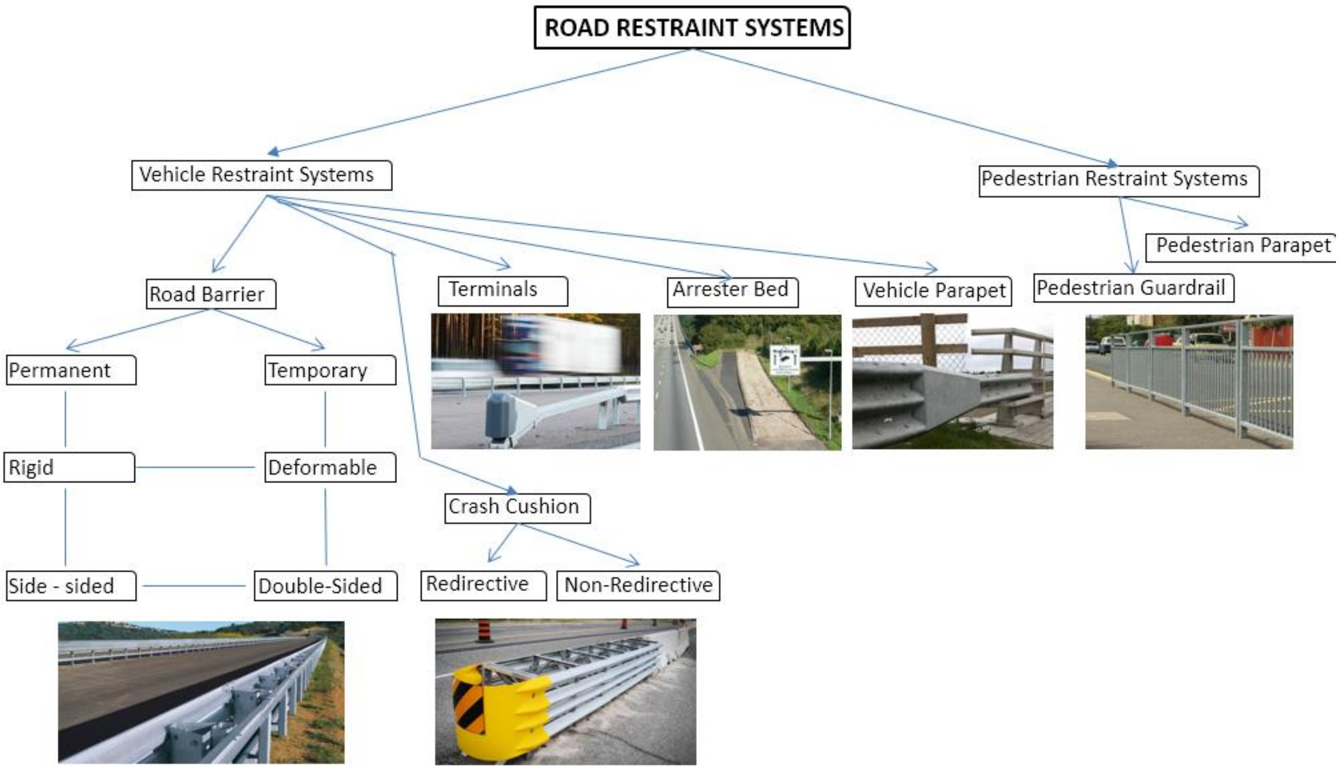


Fig. 2: Road Restraint Systems overview

2.2 Historical facts

Early road barriers have been made of concrete. Concrete road barrier design was developed in United States. First barriers were designed and tested by the New Jersey State Highway Department in 1959; the New Jersey barrier was one of the first concrete safety barrier designs to be used in large scale. During the 1960's and 1970's "Jersey Barriers" spread throughout the country and became, the most used type of concrete safety barrier. This led to the term Jersey barrier being used as a generic term, although technically it applies to a specific shape of concrete barrier.

Concrete safety barrier designs have evolved over the past fifty years to slow, redirect, or stop an errant vehicle from causing a crash with oncoming traffic or traffic in neighbouring lanes. They can be used between lanes of opposing traffic (median barrier), at the edges of roadways (roadside barrier), on bridges (bridge rail), as temporary safety barriers during construction, and in many other applications. There are multiple styles and shapes of these concrete barriers and they have changed and evolved with our highway system. They have been designed this way so that when a vehicle impacts the barrier, a significant portion of its energy is absorbed in the climbing or lifting action that occurs when the tyres roll up the lower sloping face.

Road barrier in Czech Republic

Road density in the Czech Republic as well as in the Czechoslovakia has been continuously developed just before establishing of the independent Czech state in 1918. However, boom started obviously together with the increasing numbers of the cars on the roads. The road barriers with the guardrail, as is known nowadays, have been used as late as 70´th last century. This date is closely related to the highways building. Before the highways, only concrete barriers, or stone columns with the steel rope through was used in the dangerous places.

The guardrail road barriers are one of the most used types not only in Czech Republic. The typical guardrail profile is NH4 (two square waves with the high flat central part) – see. Fig. 3. The NH4 guardrail profile was developed at the end of the 60´th by steelwork Liberty Ostrava and is used till these days with the minor changes only.

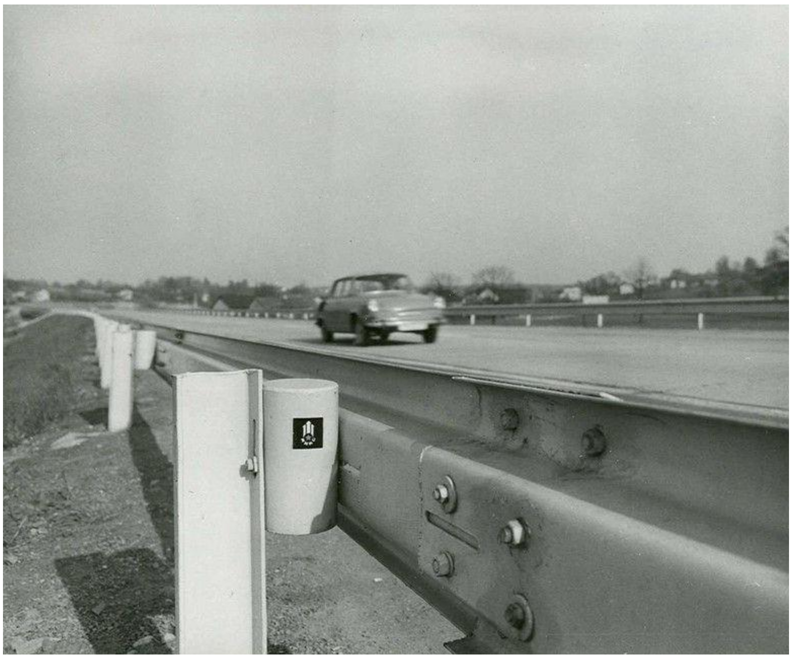


Fig. 3:Road barriers with the NH4 guardrail – used in 60th last century in central Europe

Besides the guardrail type the concrete road barriers could be used on the Czech roads and highways. The concrete road barriers started to on the Czech roads. However, concrete road barriers started to use relatively late in 90ś last century.

2.3 Road Restraint Systems legislative context

Road barriers performance shall be met for accidental design situation particularly the vehicle crash event. These structures are primary designed for accidental design situation. Other persistent or transient design situation, if exists, play minor roles.

Therefore, road barriers shall be designed to meet all the requirements imposed on them in terms of ultimate and serviceability limit states. Design of the road barriers and their parts must be capable to absorb the impact and to restraint and redirect the vehicle. The requirements for ultimate deformation and lifetime (durability) shall be met.

Various aspects must be considered when selecting the appropriate types of the road barrier. For the choice of appropriate safety measures, the restraint level, the dangerous sections of the road and the need for the protection of road vicinity must be considered.

The road barriers should fulfil many of specific requirements, including the following:

- Impact forces should be damped by the restraint system
- Soft impact of passenger cars
- Redirection of vehicles back onto the carriageway after the impact
- Overturning of vehicles should be avoided
- Deflections of the barriers should be small and within serviceability constraints
- Easy replacement of any damaged parts of the restraint system.
- Satisfy architectural and aesthetic requirements

Road barrier standards

Road barrier is a part of the road infrastructure, and therefore should be classified and assessed in term of the relevant civil engineering standards. For designing various types of the road restraint systems currently in the Czech Republic the Eurocodes and European standards EN 1317 are mandatory. The Eurocodes [2] [3] [4] should be applied to the RRS design. For the design of structures, CEN countries, including the Czech Republic, should defined National Determined Parameters (NDP). National annexes specify the application on safety requirements in the country.

EN 1990 Eurocode- Basis of design

EN 1990 [2] provides basic rules for different approaches used for the design and verification of structures. The basic design method is the partial factor method according to the Eurocodes, alternatively the probabilistic methods can be used. There are guidelines for the application of linear or non-linear methods, for the use of dynamic analyses and risk assessment methods. The ISO 2394 [6] also recommends the establishment of reliability-based design ("performance-based design"), which is also based on risk engineering methods.

EN 1991-1-7 Eurocode 1: Actions on structures - Part 1-7: General actions – Accidental actions

This Part of Eurocode EN 1991 provides indicative (minimum) requirements on quasi-static values of accidental actions due to impact of heavy vehicles into different structures in road vicinity. Standard provides information which allow to determine the impact force using probabilistic methods.

Impacting forces based on probabilistic approach lead up to three-time higher values which are not applied in structural design of road infrastructure structures. It should be also noted that simplification of the crash conditions with pure force in perpendicular direction to the RRS has a limited applicability.

In the working drafts of EN 1991-1-7 a quasi- permanent value of the impact forces (into the different construction along the road) in certain range are proposed. The lower value corresponds with current value and upper limit was app. three- times higher. This upper limit is closer to maximum sizes in the real crash. However, EN 1991-1-7:2006 (and also the final draft of EN 1991-1-7: 2021 recently developed in the 2nd generation of Eurocodes) gives minimum quasi-static impact forces only. It is advisable for CEN countries further modify these values, with respect to the national security aspect. Unfortunately, these minimum recommended forces are mainly considered in the road barrier strength design.

National requirements to the RRS – Technical Conditions and Technical- Qualitative Conditions

Technical Conditions are practical documents issued by Czech Ministry of Transportation, for designers, investors, road managers, manufacturers / importers of the road barriers and contractors, who are intended to deal with the issues of road communications. Technical Conditions are divided into:

- Technical Condition (abbreviation TP)
- Technical Qualitative Condition (abbreviation TKP)

TP and TKP also provide a basis for assessing the conformity of barriers within the meaning of Act No. 22/1997 and Government Regulation No. 163/2002. Technical Conditions can be utilized also as a guide for the product usage declaration. TP can be used for "other" road barriers as a basis to issue STO (Declaration of product conformity) by an Authorized Person.

Technical Conditions list below refers to steel road barrier design:

- TKP 11 Road barriers, Guardrails, and crush cushions
- TP 63 Steel barriers installed on the roads
- TP 101 Road barriers calculation

- TP 114 Barriers installed on the road

Technical Conditions TP 114 provides additional requests incl. the values of quasi-static impact forces and impact energy with regards to the design of the RRS. These recommended values have a deterministic character.

Two types of road barrier are given within the scope of TP 114: “approved” road barriers, which are included in [7] as construction products, and “other” road bridge barriers, which include barriers designed according to project specifications that are not repeated in individual bridges. Therefore, other barrier does not belong to the field of construction products.

For these “other” barrier designs, five categories of impact forces are introduced (with recommended forces from 100 kN to 600 kN). Moreover, the prescriptive document provides requirements for the restraining level of safety barriers for various categories of protected surroundings [8]. The requirements for verification of “other” safety barriers given in [9] are based on EN 1991-2. However, it appears that the recommended impact forces for the design of safety barriers are rather low and should be further verified.

Full scale impact testing is the most common method and only one approved for evaluating the safety performance of every new design of the RRS. Because of the multiplication of test houses in Europe and in the United states, there is an increasing need for uniformity in the procedures and criteria used to evaluate roadside safety features.

Road barrier crash test standards worldwide

The road barrier is designed for the required retaining levels, based on the relevant standards, and verified within a physical crash test. While some countries have their standards, the others adapt selected guidelines.

Most of the RRS available on the market are designed according to one of the major international standards, namely EN 1317 [7] and NCHRP 350. In Russian Federation and Armenia is used Standard GOST R52289. Australia applies the standard AS/NZS 3845:1999 Road safety barrier systems. However, this standard combines the European and US approaches and adapts it into the Australian environment. All standards provide guidelines as regards to crash testing conditions and criteria for the evaluation of roadside safety features. Fig. 4 shows the relevant Road barrier Standards and crash guideline worldwide.

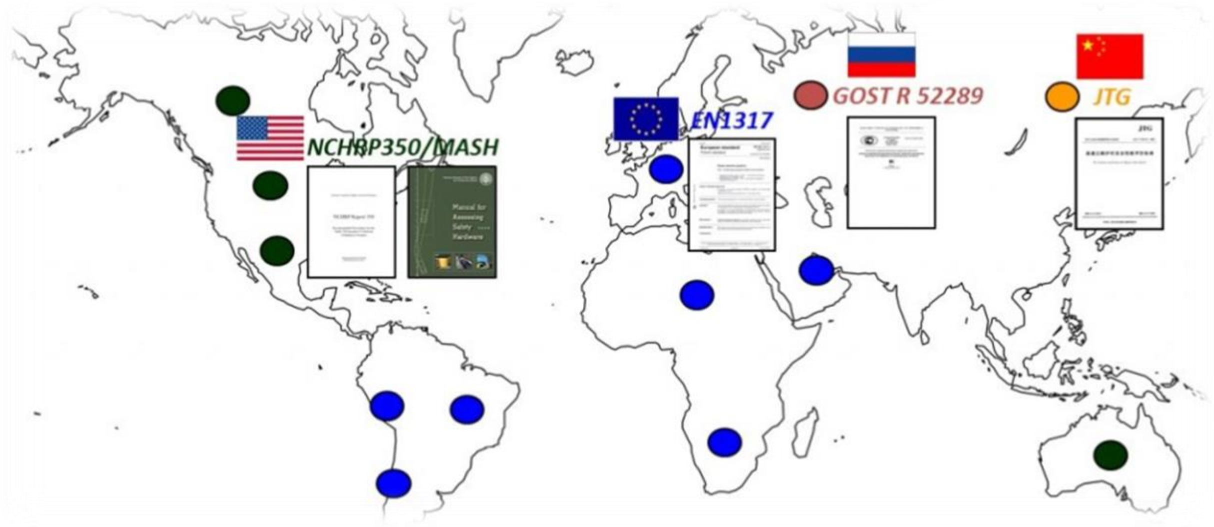


Fig. 4:Road barrier guideline Standards worldwide

American approach

NCHRP Report 350 (National Cooperative Highway Research Program) is the US standard and was used up to 2010 to certify road safety products. Currently is replaced by the MASH standard (Manual for Assessing Safety Hardware), issued by AASHTO (American Association of State Highway and Transportation). The reason of the replacement NCHRP report by MASH represents the changes in the American vehicle fleet. Vehicles have increased in size with higher position of the bumpers, especially in light trucks.

European approach

European committee for Standardization, Technical Body CEN/TC226 – Road equipment prepare specifications for safety, traffic control and other road equipment in the following fields:

- Safety fences and barriers, including guard rails, safety fences, crash barriers, crash absorbers and bridge parapets
- Horizontal signs including road studs and road markings
- Vertical signs including signs, cones and marker posts
- Traffic lights including signals, traffic control and danger lamps
- Street lighting, performance requirements only
- Other equipment including bollards, anti-glare screens and noise protection devices

Under technical commission TC226 sits sub-committees (working groups), who draft the standards using their extensive technical knowledge and experience. Working Group WG1- establish standards regarding road restraint systems which means crash barriers, safety fences, guard rails and bridge parapets.

Technical commission CEN/TC226- WG1 currently deal with many of different topics:
Moreover CEN/TC226- WG1 is responsible to prepare and take into the force the EN, TS and TR standards. Below is a pure list of the relevant Standards under WG1 responsibility:

- EN 1317- 1 to 4: 2010 - Road Restraint Systems – Part 1 to Part 4
- Harmonized Standard EN 1317-5:2007 + A2:2012 – Road Restraint Systems – Part 5: Product requirements and evaluation of conformity for VRS. In 2008 take over in Czech Republic. In 2012 the Appendix A2 has been issued. Updated draft has been submitted on the last CEN/TC226- WG1 meeting in 03/2018 in Stockholm
- CEN/TR 16949: Road Restraint Systems – Part 6: Pedestrian road restraint systems, Pedestrian parapet. Originally CEN/TR 1317-6
- prEN 1317-7: Road Restraint Systems – Part 7: Performance classes, impact test acceptance criteria and test methods for terminals of safety barriers.
- CEN/TS 1317-8: Road Restraint Systems – Part 8: Motorcycle road restraint systems which reduce the impact severity of motorcyclist collisions with safety barriers.
- Working Document WD CEN/TS 16786 – Road restraint systems – Truck Mounted Attenuators - Performance classes, impact test acceptance criteria and test methods
- CEN/TR 16303 – Road restraint systems – Guidelines for computational mechanics of crash testing against vehicle restraint system, see article 2.4.

For the approval of safety barriers, the different requirements and vehicle crash test scenarios are set in the European standard EN 1317 [7]. This harmonized standard was updated in 2011 and it is used throughout Europe. Czech Republic accepted this standard in 2011.

While Eurocodes [2] [3] [4] defines characteristics theoretical values of impact forces, standard EN 1317 defines characteristics and requirements of the RRS performance to comply. The standard [7] represents the key document for RRS testing and further CE product certification.

For the designing of the road barriers, various supplementary national codes and technical requirements are applied in the CEN Member states, including [9] the Czech Republic. These standards provide a practical guideline to apply additional demands to the RRS in order to increase or maintain the road safety level.

Fig. 5: Implementation of the EN 1317 Standard in European countries (green mark)

Standard EN 1317

The main goal of the RRS is to restraint and redirect the impact vehicle in a controlled manner. In order to assess their safety performance, the physical crash tests have to be conducted according to required restraint level (N1, N2, H1 resp. L1, H2 resp. L2, H3 resp. L3, H4a resp. L4a or H4b resp. L4b).

Restraint level is defined by manufacturer in early stage of the new RRS development phase. Restraint level (from T1 to H4b) defines the type of the acceptance tests. In most cases two crash tests are mandatory for RRS safety performance evaluation: one light vehicle used to evaluate the severity of the impact and occupants' risks and one heavy vehicle (whose weight depends on the restraint level) used to assess the crash resistance and restraint capability of the RRS. Depending on the test type the vehicle weight and test parameters vary according to the Tab. 1.

Tab. 1: Restraint level definition acc. to EN 1317 Standard

Containment level		Tests	Impact Conditions			
			Vehicle type	Impact Mass (kg)	Impact Velocity (kmph)	Impact Angle (deg)
LOW	T1	TB 21	Car	1300	80	8
	T2	TB 22	Car	1300	80	15
	T3	TB 21	Car	1300	80	20
		TB 41	HGV	10 000	70	8
NORMAL	N1	TB 31	Car	1500	80	20
	N2	TB 11	Small car	900	100	20
		TB 32	Car	1500	110	20
HIGHER	H1	TB 11	Small car	900	100	20
		TB 42	HGV	10 000	70	15
	H2	TB 11	Small car	900	100	20
		TB 51	Bus	13 000	70	20
	H3	TB 11	Small car	900	100	20
		TB 61	HGV	16 000	80	20
VERY HIGH	H4a	TB 11	Small car	900	100	20
		TB 71	HGV	30 000	65	20
	H4b	TB 11	Small car	900	100	20
		TB 81	LGV	38 000	65	20

To describe the European approach based on the Standard [7], it is appropriate to define the test demands and its evaluation criteria. These criteria could be divided into quantitative and qualitative groups.

Qualitative evaluation criteria:

Structural resistance criteria

Tested RRS should restraint the impacted vehicle and redirect them acc. to the specified redirection criteria. During and after the impact, no more than one of the wheels of the vehicle shall completely pass over or under the safety barrier and the vehicle shall not roll over (including rollover of the vehicle onto its side).

Occupants' injury risk criteria

Deformation of the vehicle interior should not cause any significant injury risk for occupants. No intrusion of the RRS parts must be observed during and after the impact. Therefore *VCDI* (Vehicle Cockpit Deformation Index) should be quantified, even if it is not crucial for final acceptance of the road barrier. *VCDI* is 9-digit code, where first two digits represents the impact side and remaining digits represents subsequently change each of the dimensions after impact, as is shown on the Fig. 6.

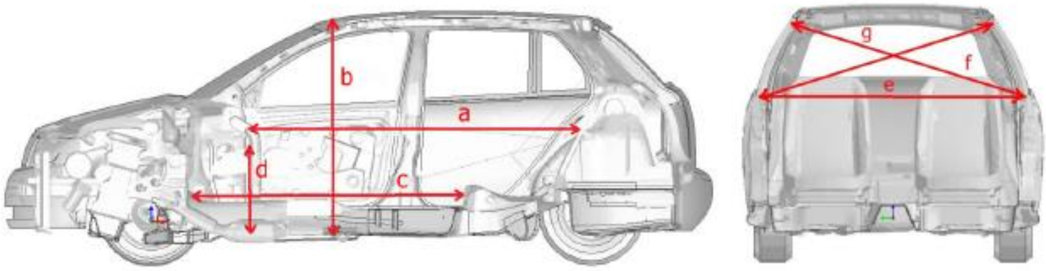
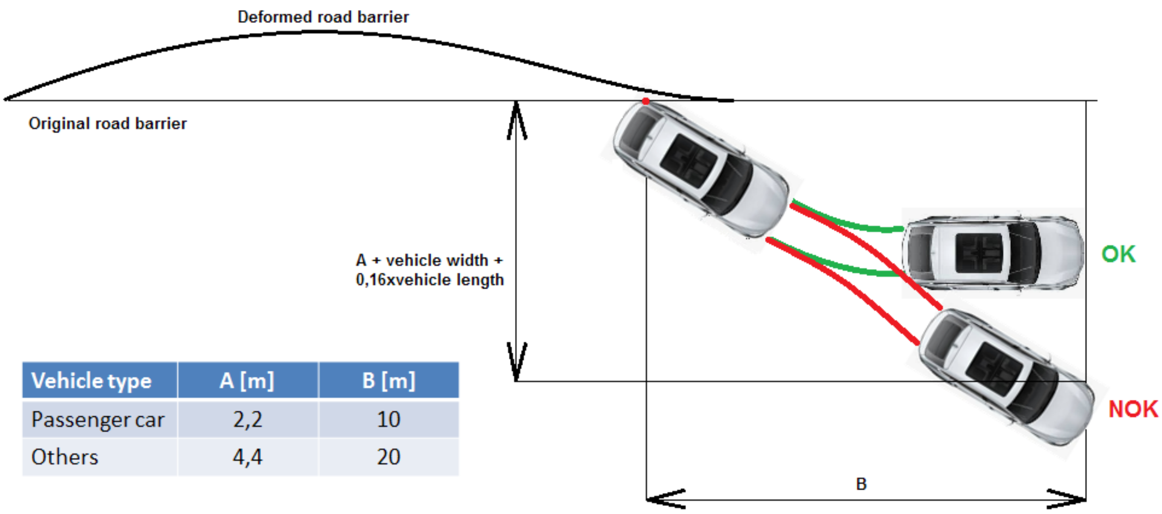


Fig. 6: Definition of the VCDI

Vehicle redirection criteria

Vehicle´s exit trajectory after impact must comply with the CEN exit box criteria. It means that vehicle after impact must leave the road barrier with acceptable trajectory of movement, for details see Fig. 7.



Vehicle type	A [m]	B [m]
Passenger car	2,2	10
Others	4,4	20

Fig. 7: Evaluation of the vehicle trajectory after impact

Quantitative evaluation criteria:

If the qualitative criteria are assessed and satisfied, the quantitative criteria are evaluated. The quantitative criteria are focused on deformation of the road barrier during and after the impact. Deformation of the road barrier is represented by dynamic deflection *D*, working width *W* and vehicle intrusion *VI*. All measured values are given in meters. The decisive value is the maximum from the test results. Dynamic deflection *D* means the maximum lateral dynamic displacement in any point of the traffic face of the restraint system and shall be measured (accuracy: ± 0.1 m) and normalized.

Working width *W* means the maximum lateral distance between any part of the barrier on the non-deformed traffic side of the barrier and the maximum dynamic position of any part of the barrier and shall be measured (accuracy: ± 0.1 m), normalized and classified (*W1* - *W8*).

Vehicle intrusion *VI* means the maximum dynamic lateral position of trucks and buses from the non-deformed traffic side of the barrier and shall be measured (accuracy: ± 0.2 m), normalized and classified (*VI1* - *VI9*). Fig. 8 shows an example for the measurements of dynamic deflection, working width and vehicle intrusion.

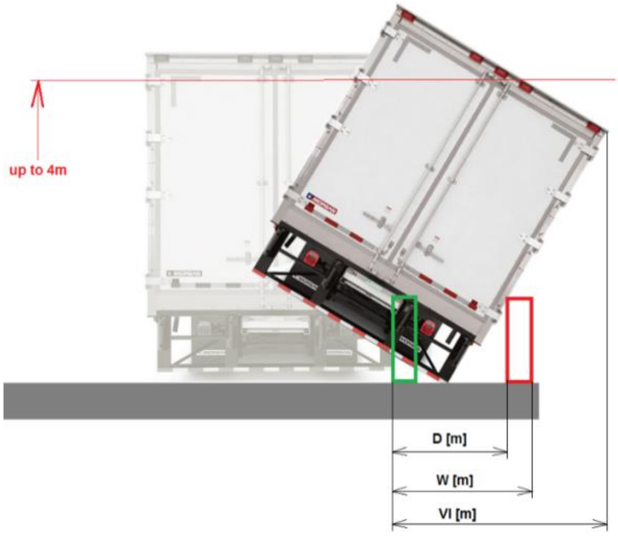


Fig. 8: Measurements of dynamic deflection *D*, working width *W* and vehicle intrusion *VI*

The following criteria are calculated from the acceleration time history measured inside the vehicle during the impact. The acceleration signal is filtered by CFC60.

Acceleration Severity Index

Acceleration Severity Index provides the measurement and evaluation of the occupant's load caused by the impact of the vehicle into the RRS. It is non-dimensional index computed from acceleration measured inside the vehicle, using the following formulae, given in [7]:

$$ASI(t) = \sqrt{\left(\frac{\overline{a_x}}{\hat{a}_x}\right)^2 + \left(\frac{\overline{a_y}}{\hat{a}_y}\right)^2 + \left(\frac{\overline{a_z}}{\hat{a}_z}\right)^2} \qquad (1)$$

$$ASI = \max\left[ASI(t)\right]$$

where:

a_x, a_y, and a_z are the 50-ms average component vehicle accelerations and $a_x\hat{}$, $a_y\hat{}$, and $a_z\hat{}$ are corresponding threshold accelerations for each component direction. The threshold accelerations are 12 g, 9 g, and 10g for the longitudinal (x), lateral (y), and vertical (z) directions, respectively. Acceleration Severity Index shall be measured (only for cars) and classified (class A-C), see Fig. 9. *ASI* shall not exceed 1,9 value.

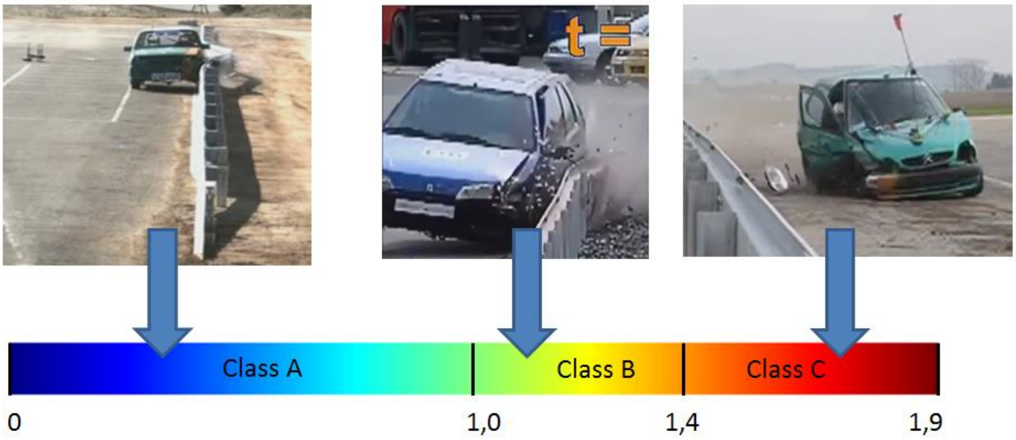


Fig. 9: Classification of the Acceleration Severity Index ASI

Tab. 2 shows the ASI level for different type of collisions and vehicles to illustrate the ASI index in general view [10].

Tab. 2: Illustrative ASI value of vehicle impacting with roadside objects

Roadside object	ASI in Car	ASI in HGV	ASI in Bus
Termination of concrete guardrail	12,7	3,8	4,2
Roadside rectangle ditch	3,9	1,5	0,2
Pole or traffic sign	2,8	1,6	0,3
Protruding rock (cubic)	7,3	7,7	2,2
Tree	8,7	4,3	3,8
Concrete barrier	3,5	3,1	2,7
W-beam steel guardrail	1,9	1,9	1,1

Theoretical Head Impact Velocity

Theoretical Head Impact Velocity (*THIV*) concept has been developed to assess occupants impact severity for vehicles involved in collisions with road restraint systems. The occupant is considered as a freely moving object (head) that, as the vehicle changes its speed during contact with the vehicle restraint system, continues moving until it hits with a surface within the interior of the vehicle, see Fig. 10. The magnitude of the velocity of the theoretical head impact is considered to assess the vehicle impact severity. Theoretical Head Impact Velocity shall be measured only for cars and does not exceed 33 km/h.

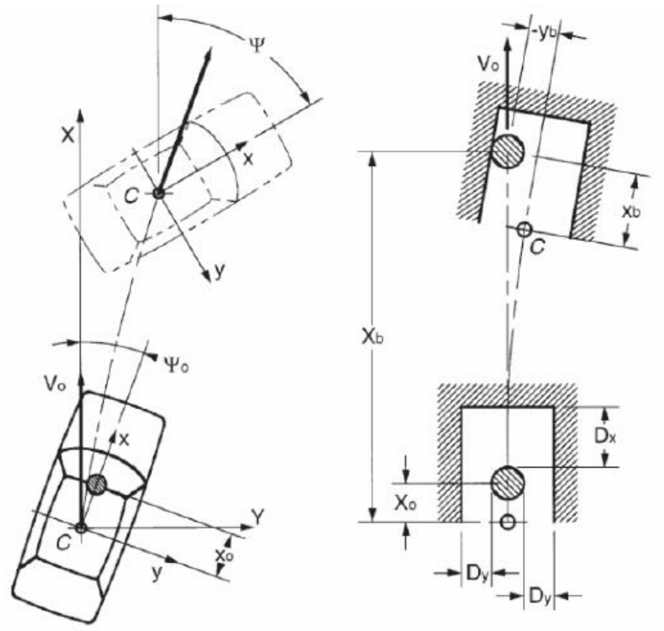


Fig. 10: Left: THIV - Reference coordinate systems
Right: Theoretical Head Impact definition

2.4 Literature survey

The literature survey belongs to kick off phase of the research work. The survey is focused to find out what kind of road barrier testing methods is currently available and whether any virtual simulations or mathematical approach have been used. Last part is focused to find out the literature dealing with HGV and LGV impact to the bridge piers or obstacles in the road vicinity.

There are many papers mentioned just road barriers physical testing or virtual simulations. However, there are the lacks to combines both. Last survey phase dealing with overview of the normative document aimed to describe and standardize the numerical modelling approach for road barrier crash tests.

1/ Standard CEN/TR 16303

To minimize the testing costs, current aim of the manufacturers as well as research institutions is to develop a methodology for substitution of the vehicle crash tests into traffic barriers by adequate computer simulation. Working group CEN/TC226 is focused to define the methodology of the computer simulation of the road barrier crash.

Standard CEN/TR 16303 [11] Road restraint systems - Guidelines for computational mechanics of crash testing against vehicle restraint system, Part 1 – 4, is focused to give guidelines in this field, provides accuracy, credibility, and confidence in the results of virtual crash test to roadside safety devices through the definition of procedures for verification, validation, and development of numerical models for roadside safety application. Standard is divided into 4 parts:

- CEN/TR 16303 – Part 1: Common reference information and reporting.
- CEN/TR 16303 – Part 2: Vehicle modelling and verification.
- CEN/TR 16303 – Part 3: Test item modelling and verification
- CEN/TR 16303 – Part 4: Validation procedures.

It is appropriate to mentioned that this document doesn’t match with current performance of FEA. Some details are described so deep and with exaggerate care, e.g. vehicle modelling and vehicle model’s verification, general FEA mesh criteria etc. Others suffer from lack of information e.g. post anchorage modelling, connection details, tyre phenomena etc. However, these aspects play key role in road barrier crash analysis.

A relatively comprehensive part of the document deals with global techniques and recommendations for FEA with fast, strongly nonlinear events. This is not necessary. It can be assumed that FE modelling activity will be done by an experienced operator who knows these criteria. In many cases the criteria are even commanded. Therefore, it would be more profitable to focus the document more on specifically road barrier crash test issues. Examples are below:

- Tyre puncture phenomena. Possible tyre puncture and discharge has significant effect to the outcome area and vehicle movement after the crash. Tyre puncture has more significant effect than steering and suspension geometry, which is comprehensive part of the document.
- Recommendation how to define the bolt connection. As a matter of fact, the typical wrench/wriggle out bolt behaviour of the main longitudinal members is common during the crash.
- Influence of the vehicle frontal part to the test results.
- Information or recommendation how to define the RRS anchorage in soil incl. the pull-out effect of the posts.
- Information or recommendation how to define the RRS anchorage in bridge parapet

Next phase of the survey deals with the crash test virtual simulation literature. Below is the citation of the most important available works, articles or project reports. Pros and contras in matter of the thesis aim complete the papers overview.

2/ Goubel C., Vehicle restraint system crash test modelling: Application to steel-wood structures. University Claude Bernard-Lyon I, 2012.
Thesis deal with the virtual simulation application for special steel-wood road restraint systems
Finally, a complete model of the road barriers is built and validated against the real crash test (Test TB32). Validated model is further used to assess the effect of wood structures on safety performance.

The proposed parametric approach, based on structure failure modes analysis, allows to get a representative model and can be easily applied to entire structure. This approach needs the identification of the failure modes and an assessment of a range of variations for the physical parameter which drive the apparition of the mechanism.

Pros of the paper:

- European approach of the testing acc. EN1317 is simple and easy described.
- US vs. EN road barrier testing approach comparison included.
- Paper includes the proposal for impact vehicle validation procedure (NCAP frontal crash etc.)
- Unique application of the simulation in wood-steel road barrier structures.
- Paper deals with failure model of the steel – wood structure in simulations.
- DOE (Design of experiment) study was defined to assess the effect of wood mechanical properties variation using 16 combinations of room temperature and moisture content.
- Simulation model was tuned (particularly the wood failure mode) according to the real test result

Contras:

- No HGV or LGV impact was considered.

3/ Schwedhelm H., Jungfeld I., Xiaochen Y., Impact of new vehicle configurations on road equipment, above all safety barriers, Deliverable report in grant project 605170: Configurable and adaptable trucks and trailers for optimal transport efficiency, BAST, 19. 05. 2017

The paper deals with the simulation in LS Dyna, using public available model of the HGV. The HGV model was updated in springs and dumpers parameters rising from VOLVO project coordinator.

Aim of the paper is focused on simulation of the TB 81 impact only. Comparison of the Simulation and real crash test data for concrete as well as steel road barrier is also included. Simulations results have been compared if comply with the tolerance limits in CEN/TR 16303-4: 2012 and draft standard prEN 16303:2016.
Differences are more conservative. However concrete road barrier is not aim of this thesis therefore results differences cannot be compared.
Paper also contains with the simulation scenarios significantly different conditions from nominal test EN1317. In test was LGV overloaded to 40 tons or 41 tons up to 42 tons. Impact to the test results was assessed. There are a few pros and contras arise from the paper.
Pros:

- Dealing with simulation comparison to the real crash test.
- HGV model data available.
- Concrete road barriers modelling features are mentioned.
- Study of the overloaded HGV impact to test result. This feature is similar to model uncertainties study in this thesis.
- Vehicles COG position in Z direction represents a protentional risk of the vehicle rollover.

Contras:

- Paper deals with one test scenario only,
- Simulations utilize the public available vehicle model only.
- Analysis was done in LS DYNA simulation sw. (as many others)

4/ Zou, Y., Tarko, A. P. (2016). Performance assessment of road barriers in Indiana (Joint Transportation, Research Program Publication No. FHWA/IN/JTRP-2016/12). West Lafayette, IN: Purdue University. http://dx.doi.org /10.5703/1288284316335
Main contribution of this paper with regards to the thesis aim could be found in description of the soil modelling approach. Even if the models were prepared in LS DYNA software, the essential principles could be implemented in other simulation software as well. Also, the crash test approach comparison between EN1317 and NCHRP 350 vs. MASH is beneficial.

5/ Tso-Liang T., Cho-Chung L., Thanh-Tung T., Effect of various W-beam guardrail post spacings and rail heights on safety performance,, Advances in Mechanical Engineering, 25 September 2015

This paper deal with analysis of the steel road barrier impact test results for different height of the guardrail and post spacing. Baseline model is developed and further validated against real crash test. Effect of the post spacing (post pitch 1333, 2000 and 4000mm), W-shape beam guardrail height (600,650,700,750, 800 and 820 mm) on road barrier safety performance were evaluated in paper. EN1317 crash test criteria didn't meet for maximal height of 820mm – vehicle had tendency to underrun the W beam guardrail.

Pros:

- FE simulation is validated against real crash test, therefore relative difference is available.
- Good math of the simulation model, except THIV parameter. This corresponds with thesis outcomes.
- Boundary conditions and initial conditions are described in detail.
- The post support in soil modelling approach is proposed.
- Overview of the FE modelling lightweight vehicle impact for the typical steel road barriers.

Contras:

- Paper framework is limited to one test TB 11 scenario and one road barrier type (W beam – type A) only.
- Road barrier model is simple and use simplified material model.

- No effect of the heavy vehicle impact was considered in thesis, even if it is crucial for road barrier containment performance.

6 /Project ROBUST (2003-2006)

In the thesis context is reasonable to mention the European project ROBUST (Road Barrier Upgrade of Standards) [12] [13]. This European project, coordinated by Polytechnic University of Milan, is focused to demonstrate if road barrier crash tests conducted in two different testing facilities could be comparable in results. Research activities of the project include collection of data from real life accidents, from full scale crash tests and to answer several open questions such as:

- How crash tests represent real life conditions?
- How computational mechanics can be used to improve tests effectiveness?
- Will the use of vehicles of different manufactures, with mass and dimensions within the tolerances specified by the standards, produce consistent result?

Project outputs shows that a crash test configuration can be repeated in two different test houses with highly comparable results but with a high level of control of input parameters (car model and age, impact condition, anchorage conditions, etc.). Checking all variable and parameters requires a high effort to control the entire process therefore cannot be fully guaranteed in all test houses.

Even if the outputs have no direct impact to this thesis, it is obvious that uncertainties associated with the physical testing could be conditionally minimised. Therefore, these uncertainties are not taken into account in this thesis.

There is more information available in contributions dealing with impacts to the bridge piers imposed by heavy goods vehicles (HGV). Also a few Czech research articles can be found, e.g.

7/ Jiříček P., Foglar M., Numerical analysis of a bridge pier subjected to truck impact, CTU in Prague, Fac. of Civil Engineering, Prague; CZ.

This paper describes the contribution from 18th International Conference ENGINEERING MECHANICS 2012 in Svratka, Czech Republic. Even if the paper was issued in 2012, essential principles described here are still valid.

In paper were assessed many different approaches to vehicle impact, incl. normative approach of vehicle impact from EN1991-1-7 and accidental load combination. Article deals with the numerical simulation of the bridge pier loaded by equivalent static force from EN 1317. Nonlinear numerical analysis was done in ANSYS sw. and models were created in AUTODYN sw.

Clear presentation of the impact force time history seems to be a main advantage of the article. Contrary no road barrier protection was considered in analysis. Only one test scenario (closely to Test TB81 – HGV with 32tons) were analysed in paper.

8/ Ruiwen D. Z., Li, J.W., Guo Ch., Study on Impact Behaviour and Impact Force of Bridge Pier Subjected to Vehicle Collision, Research Institute of Structural Engineering and Disaster Reduction, Tongji University, Shanghai, China, 16 July 2017

In this study, the vehicle-pier collision numerical model was developed in LS-DYNA and validated. Nonlinear material constitutive laws considering strain-rate effect were used. Based on the validated numerical model, parametric studies were carried out to investigate the effect of impact velocity, impact mass and concrete and steel strength on the impact behaviours of the impact piers and the impact forces. The relationship between failure modes of piers and impact energy was analysed.

2.5 Literature survey outcomes

There are several outcomes and inputs, we can evaluate from available literature and consider in work.

- All numerical models in papers were post tuned to provide as best match with real crash test as possible. No paper shows the simulation models verification in case that physical test results are not known in advance:
- No simulation of HGV impact was validated
- Most of the simulations were done in LS DYNA sw. perhaps, due to the public vehicle models availability. No simulation analysis was done in Pam Crash sw.
- There is enough information on the lightweight vehicular impact. Therefore, dealing with the passenger car impact simulation in detail is not necessary.
- Detailed and verified model of the impacting vehicle is essential in case of the test TB11, otherwise the occupant's injury parameters suffer with significant error. This feature is common for many papers.
- No list with content of the real crash test inputs and results is not available and likely has never been done.
- No road barrier crash test model uncertainties have been analysed in papers
- Most of the papers deal with limited numbers of the road barrier crash scenarios.
- No papers mentioned the analytical approaches as equivalent impact event solution.

Some features of the modelling approach are common for all papers, others are unique and some of the topics provided in this thesis have never been solved.

3 Impact to the road barriers and obstacles

3.1 Normative context of accidental impact load

Main aim of the analytical impact model is to determine the magnitude of impact force into the object or obstacles. This force is further used for the design e.g., bridge supporting structures, posts in road vicinity and initial design of road barriers as well. Therefore, the load on a structure from impact is typical accidental load from the standard´s point of view. However, the response of the structure subjected to impact load is a complicated highly non-linear process since large displacements, deformations, non-linear material behaviour and contacts with friction are likely to occur.

According to the Eurocode EN 1990 and the other normative documents, the partial factor method, linear or non-linear approach as well as probabilistic methods and risk engineering methods can be applied for the design and verification of structures.

Eurocode EN 1991-1-7 gives recommendations for accidental impact load models from vehicles into various types of structures, such a bridge pier, walls, supporting structures, superstructures and road barriers as well. According to this standard, the effects of impact loads on structures can be determined based on different methods:

- Quasi-static approach based on equivalent static force
- Dynamic analysis
- Probabilistic methods
- Risk engineering methods.

For accidental design situations, the structures are categorized according to the expected consequences into three consequence classes (CC):

- CC1 - small consequences of failure - verification that robustness and stability according to EN 1990 to EN 1999 are met.
- CC2 - medium consequences of failure - a simplified calculation with static models is usually used or standard design rules may be applied.
- CC3 - major consequences of failure - analysis are performed for the specific case to determine desired reliability level of structure (e.g., includes dynamic analysis, a nonlinear model and considering the interaction between load and structure).

Actions specified in EN 1991-1-7 are classified as accidental actions. In usual cases, they are considered to be free loads. To verify the structure for accidental loads, including vehicle impact, the equation 6.11 according to EN 1990 is used. The accidental load is combined with permanent loads and other variable loads. The partial factors of all loads (permanent, variable and accidental) are equal to one. Then for the most effective accompanying variable load, a frequent value of this load is applied.

The basic quantities for impact analysis are the velocity of the object causing the impact, the mass distribution, the deformation characteristics and damping characteristics of the impact object and the structure. Moreover, it is necessary to know the other factors such as the impact angle, the impact object structure and its movement after impact. To determine the material properties of the colliding object and structure, it is necessary to use the upper and lower characteristic values. The strain level of the structure should be also considered.

3.2 Eurocode equivalent static force approach

Eurocode approach is suitable for the structures where energy is already dissipated by impact vehicle. Pure static forces are defined in Tab. 3 [3] for impact into the supporting structures and Tab. 4 [3] for impact into superstructures.

Except the equivalent force value, the contact patch dimension is also proposed. The dimensions masses and other characteristics of the impact vehicles are summarized in informative Annex C of EN 1991-1-7.

Tab. 3:Indicative static equivalent design forces from vehicle impacts on supporting structures, EN 1991-1-7

Type of road	Impact force F_{dX} (kN)	Impact force F_{dY} (kN)
Motorways (Highways and 1st class roads)	1000	500
2nd class roads	750	375
Urban Roads	500	250
Closed traffic areas: - Cars - Heavy vehicles	50 150	25 75

Design values of accidental impact loads F_{dx}, F_{dy} (longitudinal and transversal components of contact force F_0) on supporting structures located in the road vicinity (e.g., columns and walls of bridges or buildings) should be determined according to the consequences of the impact, the expected intensity, the traffic and the consequence mitigation measures. Guideline for risk analysis is given in Annex B of EN 1991-1-7.

Rules for the application of impact forces F_{dx} and F_{dy} on structures can be specified in the National Annex or individually for the project. According to EN 1991-1-7, the simultaneous action of the impact forces F_{dx} and F_{dy} does not have to be assumed. For an impact to the support structure, the contact area of the impact force F is determined, shown in Fig. 11.

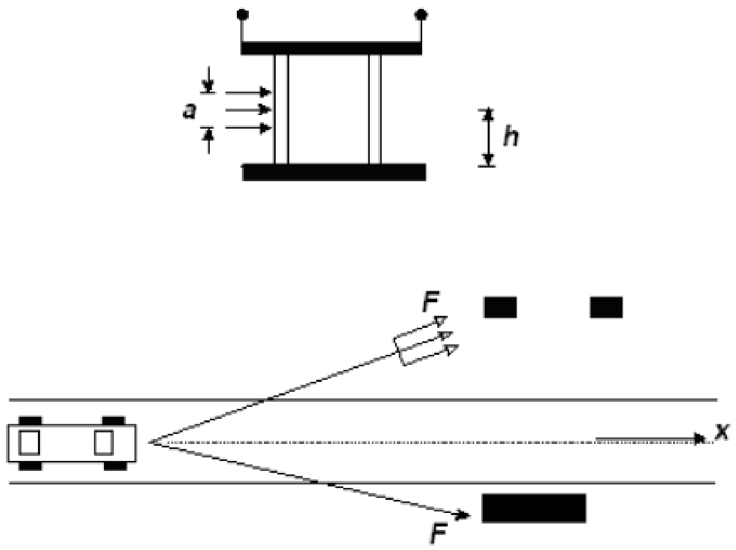


Fig. 11:Impact force due to vehicular impact on supporting structures in road lane vicinity for bridges and supporting structures

Tab. 4:Indicative static equivalent design forces from vehicle impacts on superstructures, EN 1991-1-7

Type of road	Impact force F_{dx} (kN)
Motorways (Highways and 1st class roads)	500
2nd class roads	375
Urban Roads	250
Closed traffic areas:	75

Impact force from HGV and LGV may be applied at any height from 0,5m to 1,5m above the road. The force may be applied higher if the road barriers are provided. The recommended contact force area (rectangular shape) has height *a* = 0,5m and width 1,5m or the structure width whichever is the smaller. Impact force from passenger cars may be applied at height 0,5m above the road. Recommended contact force area is the same.

3.3 Eurocode dynamic force application

In dynamic analysis, the interaction with a moving object and a structure is considered. There is a sudden conversion of the kinetic energy of the moving object into deformation energy of the structure and object. The dynamic analysis principles are given in EN 1991-1-7, Annex C. This annex provides guidance for the approximate design of structures subjected to exceptional impacts from different types of vehicles. Simplified or empirical models are significantly employed.

Eurocode EN 1991-1-7 differentiates between soft and hard impacts. Hard impacts are considered for structures in road vicinity (buildings, bridge piers etc.). In this type of impact, it is usually assumed that all the energy is absorbed by colliding object (vehicle). However, this assumption generally leads to conservative results.

Soft impacts are considered for structures as road barriers, which are designed to absorb the energy of the impact through elastic-plastic deformations of their elements. The equivalent static load (pure force) can be determined here by considering both the ultimate plastic strength and the deformation capacity of these elements.

Hard impact

It is assumed that structure is not moving and is more or less rigid. The impacting object is deforming in linear scale. The EN 1991 hard impact models consider a perfectly flexible object (impact vehicle) and rigid barrier (wall, bridge pier or obstacle). All initial kinetic energy of the moving vehicle is transforming to the potential elastic deformation energy of the barrier in time of the maximal impact force peak.

Therefore, the following relationship can be given

$$Wo = \frac{1}{2} m_1 . v_0^2 = \frac{1}{2} . F . \Delta L \quad (2)$$

Where the deformation of the impacting objects and impact force are in relation (for linear elastic object):

$$F = k . \Delta L \quad (3)$$

Stiffness coefficient k could be written for impact object with parameters A, L and E:

$$k = \frac{E\ A}{L} \quad (4)$$

where:

E	means the Elastic modulus
A	means the cross-section area of the impact body
L	means the impact body length

Finally, we get the maximal value of impact force as is shown in EN 1991-1-7 in form:

$$F = v_0 . \sqrt{k . m} \quad (5)$$

And for impact object mass is:

$$m = A . L . \rho \quad (6)$$

where:

v_0	means the impact velocity
k	means the equivalent body stiffness (F over the total deformation)
m	means the impact body mass
ρ	means the impact object density

The load on the structure is considered as a rectangular impulse with a given time duration.
Alternatively, a linear increase in force can be used as it is shown in Fig. 12.

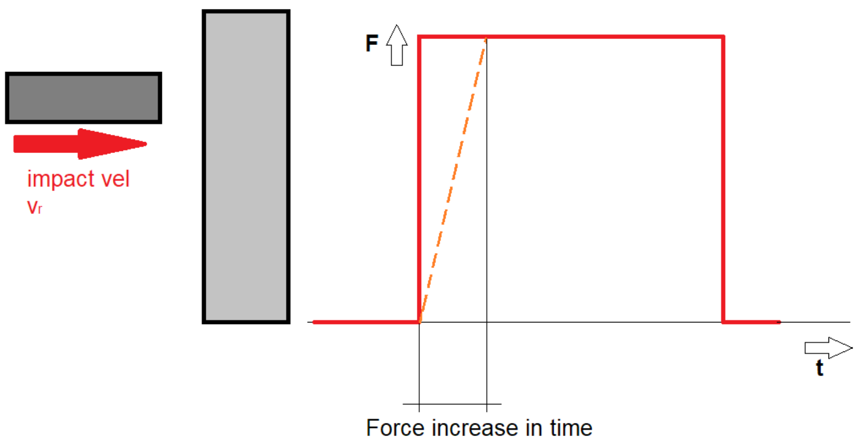


Fig. 12:Impact force due to vehicular impact on supporting structures

Hard impact approach has certain limits. For instance, while colliding vehicle is modelled as a spring with constant unchanging cross section and linear deformation. This is considerably simplified assumption.

Soft impact
Soft impacts are considered for structures which are primary designed to absorb the energy of the impact through elastic-plastic deformations of their elements, e.g. road barriers, crash cushions and terminals. It is assumed that the structure is designed so that it can absorb all the kinetic energy of the impacting vehicle due to its sufficient deformation capacity. At the same time, it is assumed that the impacting vehicle is rigid.

If we consider only the plastic structure response, the condition of the impact energy absorption can be written:

$$\frac{1}{2}.m.v_r^2 < F_0.y_0 \qquad (7)$$

where:
F_0 means the plastic deformation limit of the structure
y_0 means deformation capacity or deformation in impact point

Note:
If the structure is considered flexible and impact body rigid the Hard impact approach may be applied, where k means the structural stiffness (not the stiffness of the impact body).

3.4 Energetic approach

Energy equilibrium-based theories could be utilized for the impact of the vehicle into the road barrier or other obstacles, even if it is not mentioned in EN 1991-1-7. Such approaches are provided on the body impact theory and practically used until these days.

Despite their obvious imperfections, they can provide a rough estimate of results in cases where exact solutions are very complex or difficult.

However, there are some limiting factors common to all impact concepts, particularly:

- Static deformation curve expresses material behaviour under dynamic load too. Unfortunately, the dynamic deformation characteristics are significantly different. Main difference arises from strain rate effect of the material resistance. More details are shown in article 4.5. Engineering stress-strain diagram for different loading speed are shown in Fig. 23.
- Deformation characteristics of the material has no failure mechanism. Failure of the material under dynamic deformation is not considered, for steel stress-strain diagram see Fig. 13.

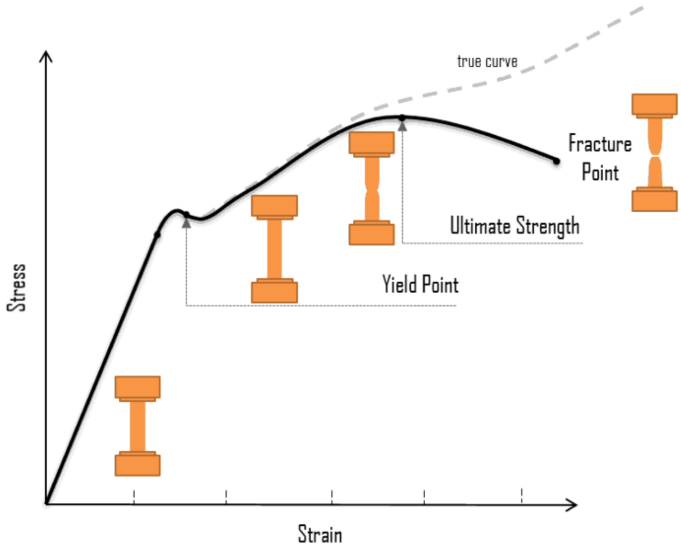


Fig. 13:Steel stress-strain diagram, source: www.researchgate.net

- Impacting object stiffness over the deformation is constant (linear spring stiffness), respectively bilinear (elastic-plastic impact). This represents a significant simplification of real impact with real vehicles.

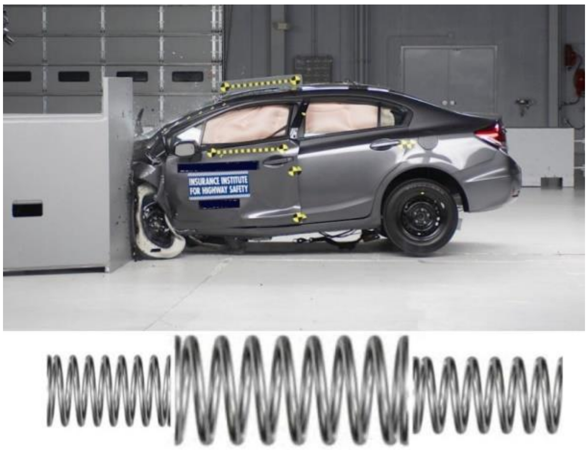


Fig. 14:Real vehicle under impact - parallel springs simplification

Further these models can be supplemented to the elastic-elastic as well as elastic-plastic impact concept. There are also other concepts beside next two approaches, e.g. elastic-plastic-rigid impact concept etc. Examples of two concepts below have a potential to be considered in initial analysis with no extreme demand on input data. [14]

The impact of the objects based on the energy theories was already described in [15] .

Elastic only and elastic-elastic impact concept [15]

In EN 1991 the energy balanced model is initial kinetic energy, which can achieve (depending on initial velocity v_0) any value and on the other side there is elastic strain energy, accumulated in object. The value of this energy is limited by material properties.

Therefore, conversion of whole initial kinetic energy into potential deformation energy cannot exist and certain constraints need to be set.

The limiting factor for maximum deformation capacity is the material yield strength σ_T. Then, for the maximum impact force applies

$$Ft = \sigma_T A \qquad (8)$$

where:

A means the impact object cross section

σ_T maximal stress (yield strength)

With respect to previous relations, we can express the maximal initial impact velocity, when deformation capacity is reached.

$$v_m = \sigma_T \frac{A}{\sqrt{mk}} \qquad (9)$$

If the initial velocity v_0 is higher, then the energy conversion is realized in a different way. Impacting object does not have sufficient deformation capacity to accumulate the kinetic energy of the impact. The impact time Δt we can express from impulse theorem and change of momentum theorem:

$$\Delta t = 4.\sqrt{\frac{m}{k}} \qquad (10)$$

Note: For time $t = \Delta t$ the accumulated deformation energy suddenly changes back to kinetic energy and the object bounces off the rigid wall at the same velocity with opposite direction. It is obvious that this concept is quite far from reality.

Elastic- elastic impact concept [15]

Pure elastic concept could be sufficiently extended to elastic – elastic impact concept, where both colliding objects cooperate. Impacting objects can be modelled as springs representing the material properties. We can also define a spring with stiffness constant k_1 for a moving vehicle and a spring with a constant k_2 for road barrier. With respect to position of the objects just in the impact point is advisable to consider the serial springs arrangement, i.e. one behind the other. Deformation for serial springs arrangement could be expressed with respect to relation (4):

$$\Delta L = F\left(\frac{1}{k_1} + \frac{1}{k_2}\right) \qquad (11)$$

From total energy balance and initial kinetic energy formulae $W_0 = 1/2\ m.v_0^2$ the maximum impact force values are gained:

$$F = v_0\sqrt{\frac{m_1 k_1 k_2}{k_1 + k_2}} \qquad (12)$$

In case of parallel springs, we can express the time of the impact:

$$\Delta t = 4\sqrt{m_1\left(\frac{1}{k_1} + \frac{1}{k_2}\right)} \qquad (13)$$

Elastic-plastic impact concept [15]

Dissipation effect in both impacting objects needs to be considered when elastic-plastic impact is analysed. Thus, deformation effect on the obstacle should be different comparing to other concepts (e.g. plastic only concept or elastic-plastic- rigid concept). Plastic state in the moving objects exists when maximal impact force has been reached. If the maximal impact force F is the force when plastic deformation has been reached F_T we can assume:

$$F_T = \sigma_T \, . \, A \qquad (14)$$

We assume that I_1 represents the impulse of the impact force in increasing zone of the F-t diagram. In the same manner we assume I_2 as impulse of the impact force in decreasing zone of F-t diagram. We can use the restitution coefficient to compare both impulses as follows:

$$I_2 = \varepsilon \; I_1 \qquad (15)$$

According to the impulse theorem and change of momentum theorem applied on moving objects the following formulae can be written for any moment t of impact:

$$V(t) = V_0 - \frac{I(t)}{m_1} \quad (16)$$

For second part of the impact (decreasing zone of the impact force) is given:

$$v_1 = V_0 - \frac{1+\varepsilon}{m_1} I_1 \quad (17)$$

where:
v_1 means the velocity in time t
v_0 means the initial impact velocity
ε means restitution coefficient
m_1 mass of the impact object

The change of the kinetic energy theorem could be written with regards to previous formulae:

$$\frac{1}{2} m_1 ({v_0}^2 - {v_1}^2) = \sum W \quad (18)$$

where:
W – means the total work incl. the energy dissipation
From relation (17) we obtain (both sides of the equation are multiplied by v_1 and v_0):

$$v_0 + v_1 = \frac{1}{I} m_1 ({v_0}^2 - {v_1}^2) \quad (19)$$

Finally, there is an expression combines the *Change of the Momentum* and *Impulse theory*. These two main theorems are usually used when solving the impact phenomena:

$$(1+\varepsilon) I_1 = m_1 V_0 - m_1 \sqrt{{v_0}^2 - \frac{2\sum W}{m_1}} \quad (20)$$

According the F-t diagram and expression [20] we can get the total impact time for elastoplastic concept of the impact:

$$\Delta t = \frac{2(1+\varepsilon) m_1 I_1}{\sigma_T A} \quad (21)$$

This time can be divided into two phases - increasing t_1 and decreasing t_2 zone in *F-t* diagram

3.5 Probabilistic analysis of the impact force

General information on impact forces and probabilistic models of basic variables are detailed in Annex C of EN 1991-1-7. In this case, it is based on the probability requirement for which the maximum impact force from vehicles should not be exceeded.

If the recommended values of probabilities according to Eurocodes and ISO standards are considered, then the resulting values of impact forces are in the upper range of, which were given in draft of EN 1991-1-7, i.e. from 1000 to 2500 kN, depending on the type of road and characteristics of the impacting body.

3.6 Structure reliability and probabilistic assessment principles

Basic approach of the probability assessment is specified in Eurocode [2]. The principles could be used in specific cases for structure reliability assessment including the RRS. The probabilistic model is entering the limit state function. The following formulae give failure probability P_f.

$$P_f = \int_{G(X) \leq 0} f_X(x) dx \quad (22)$$

where $f_X(x)$ is the combined probability density for realizing the vector $\boldsymbol{x}$ of the basic quantities. The reliability index is defined based on failure probability P_f as follows:

$$\beta = -\Phi^{-1}(P_f) \quad (23)$$

where Φ denotes the Normal distribution function. The probability P_f and the reliability index β are fully equivalent reliability indices. The relationship between the probability of failure and reliability index is shown in the Tab. 5 .

Tab. 5:The relationship between the probability of failure P_f and reliability index β

P_f	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
β	1,3	2,3	3,1	3,7	4,2	4,7	5,2

In many cases it is possible to express the limit state function by two separate basic variables X_1 and X_2 (the member resistance R and the load effects E) by the following formulae:

$$g(R, E) = 0 \quad (24)$$

The probability of failure P_F or reliability index β is compared to the reference (target) value of the probability of failure P_{ft} or reliability index β_t. It is assumed that the structure is reliable when the following condition is met

$$P_f < P_{ft}\text{, resp. } \beta > \beta_t. \quad (25)$$

Reliability of the road barrier structure can be solved analytically, e.g., by approximate analytical methods, numerical methods of integration, simulation methods or combinations [16] [6].

The representative value of an accidental load is determined so that the relevant or higher energy from the accidental load occurs with an annual probability of at most $P_{tA} \leq 10^{-4}$, in accordance with ISO 2394. Two independent design situations should be considered in case of the road barriers and similar structures. For probability of the standard design situation N and accidental design situation A could be defined $P_N + P_A = 1$. Thus, with regards to the statement of complete probability, we can define the failure probability of the structure as:

$$P_f = P_{fN}\, P_N + P_{fA}\, P_A \cong P_{fN} + P_{fA}\, P_A \quad (26)$$

Impact into the structure is the typical accidental situation for the road barriers. Standard design situation is negligible in case of typical road barriers. Nevertheless, in case of special road barrier design which combines other functions e.g., noise barrier the design situation could represent the significant contribution for the structural loading.

Approximation indicated in the equation (6) can be carried out. The probability of the accidental design situations P_A is usually very small and the probability of the permanent design situation P_N is app. unitary, thus $P_N = 1 - P_A \approx 1$.

We assume that the overall probability of the failure is limited by the target value P_t (1,3. 10 $^{-6}$ per year), then the probability of structural failure P_{fA} should satisfy the following condition:

$$P_{fA} \leq \frac{P_t - P_{fN}}{P_A} \quad (27)$$

Using the probabilistic methods, it is possible to define the conditional probability of the failure (e.g. road barrier of bridge column) alongside the road, with the presumption of the accidental design situationP_{fA} could be specified for structure.

The conditional probability of the structural failure with the estimation of the standard design situation P_{fN} is also possible to be specified.

3.7 Eurocodes and JCSS probabilistic impact model

Basic principles for structural design in accidental situation are stated in Eurocode EN 1991-1-7. Eurocode document describes the vehicular impact forces values to the bridge piers and obstacles (hard impact), as well as other structures like a road barrier (soft impact). Therefore, Eurocodes provide overall information, to determine the impact forces based on the probabilistic approach.

Fundamental problem of analytical modelling is to determine the initial conditions of impact. It means, the mass, velocity and angle of the impacting object (vehicle). It is appropriate to use already existing models used in Eurocode and other documents [3] [17] [18] .

With help of the vehicle deceleration and road lane leaving mathematical model, we can describe the pre-crash conditions. The mathematical model is based on the Eurocode [3] for accidental loads and the principles of the JCSS Manual [18]. Based on the statistical data and collision probability, the accidental impact load can be determined.

Initial data for accidental impact load in JCSS Probabilistic model code [18] covers:

- Object is moving in defined distance from traffic lane and can potentially impact to the obstacle.
- Existence of human or mechanical fault leading to the vehicle lane leaving. Poisson distribution describes this event.
- Object movement direction after initial fault
- Collision with the structure or obstacle

Initial velocity v_0 and angle α are the main characteristics which describe the vehicle movement and pre-crash conditions. There is no evidence of the dependency between v_0 and α for straight sections of the road. The impact angle varies from 0° to 30°, in extreme and rare cases up to 40°. In most countries, statistics are available for different types of roads, especially highways. According to the guideline [6], the probability of the car highway leaving is app. 10^{-7} per vehicle and km. The real value may be higher or lower, depending on local conditions, e.g., the vehicle speed, type of road, vehicle weight, local weather conditions and traffic intensity at daytime.

The vehicle usually decelerates behind the point of track leaving due to the road obstacles or driver interference. It is assumed, that vehicle keeps its movement and direction. The velocity v(t) and distance $r(t)$ are calculated as a function of the time t.

$$v(t) = v_0 - at \tag{28}$$

$$r(t) = v_0\, t - \frac{1}{2}at^2 \tag{29}$$

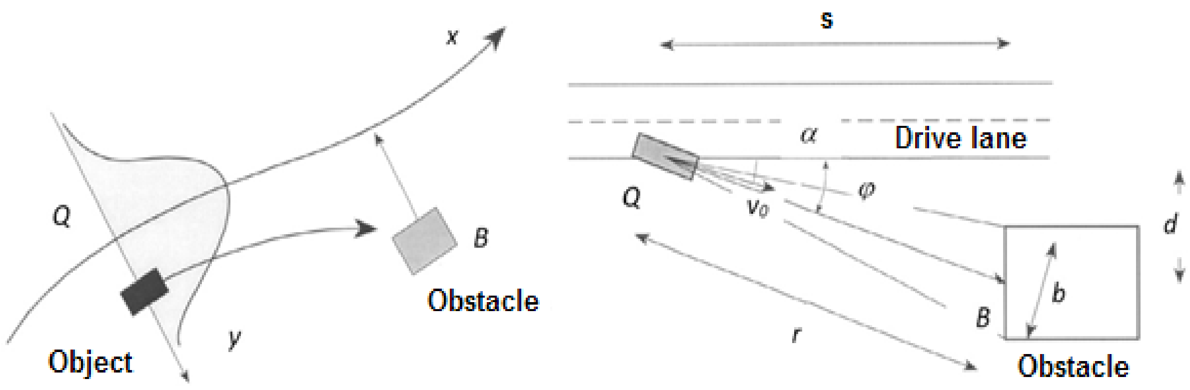


Fig. 15: Probabilistic model of the vehicle lane leaving and collision into the obstacle by JCSS

The probability of the vehicle collision with the obstacle (e.g., structural member, pier or road barrier) could be defined using the model of the vehicle lane leaving and the model of collision with obstacle. The limit state function is based on the determination of the reliability margin $Z(r,e)$:

$$Z(r,e)= R - E \qquad (30)$$

Structural resistance R is the static equivalent value of the design force F_d, according to [3]. Load effect E can be based on the simple impact force model to determine the impact force, as described in [3], Annex C. The vehicle is substituted by elastic beam (mass m and stiffness k). Then maximal interaction force is:

$$F= \sqrt{m.k.v_r^2} = \sqrt{[m.k.(v_0^2 - 2as)]} \qquad (31)$$

Determination of the impact velocity:

$$F= \sqrt{(v_0^2 - 2as)} = v_o\sqrt{1 - d/d_b} \text{ (for } d < d_b\text{)} \qquad (32)$$

where:

v_o is the heavy vehicle speed when leaving a lane
a is the average deceleration after lane leaving
s is the distance between the lane leaving point and obstacle
d represents the distance between the lane centre line and obstacle
d_b represents the braking distance $= (v_o^2/2a)\sin\varphi$, where φ is the angle between the lane centre line and vehicle movement direction

Recommended values together with a suitable probability distribution are shown in Tab. 6.

Tab. 6: Probabilistic calculation of the impact force acc. to EN 1991-1-7

Basic variable	Place	Probability distribution	Mean	Standard Deviation
v_o	Vehicle speed –highways –Local roads	 Lognormal Lognormal	 80 km/h 40 km/h	 10 km/h 8 km/h
a	Deceleration	Lognormal	4 m/s^2	1,3 m/s^2
m	Vehicle mass – heavy	Normal	20 000 kg	12 000 kg
m	Vehicle mass – cars	–	1 500 kg	–
k*	Vehicle stiffness*	Lognormal*	300 kN/m*	60 kN/m *
φ	Impact angle	Raleigh	10°	10°

* The probability model of the vehicle stiffness is shown in the JCSS Probabilistic model code [4]

Tab. 7:Design values for vehicle mass, velocity, and dynamic impact force F_0

Type of road	Mass m (kg)	Velocity v_0 (kmph)	Deceleration a (m/s^2)	Impact force F_0 (kN)	Distance d_b (m)
Motorways (Highways and 1st class roads)	30 000	90	3	2400	20
2nd class roads and roads with the speed limit exceeds 50kmph	30 000	70	3	1900	20
Urban areas (speed limit is 50kmph)	30 000	50	3	1300	10
Closed areas (factory yards etc.) - Cars	1500	20	3	120	2
- All vehicles	30000	15	3	500	2
Parking garages - cars only	1500	10	3	60	1

3.8 Annual probability of the structure failure

Residual risk is specified in EN 1991-1-7 [3]. Structure cannot be designed to withstand all possible accidental loads. Residual risk is related to the accidental load with relatively low probability of existence. These risks are likely not respect in the original design of the structure as well as other loads which are well known, but small risk should be accepted in design concept.

Once, residual risks are assessed the costs of the relevant safety measures compared with the consequences of the serious failure should be considered. The potential reaction of the public to an adverse event needs to be considered as well.

Annual maximal acceptable probability of the structure failure is expressed acc. to [6].

$$P_f < 10^{-6}/p(d/f) \qquad (33)$$

where $p(d/f)$ is the probability of fatalities due to the specified structure failure. Probability $p(d/f)$ highly depends on the time when peoples are present inside the structure or their dangerous vicinity.

Annual maximal acceptable probability of the structure failure based on the risk optimization with regards to the human life should fulfil acc. to [6] the condition:

$$P_f < A.\ N^{-k} \qquad (34)$$

Where N is the expected number of deaths per year. For the variables A and k variables are following values are recommended A = 0,01 to 0,1 and k = 1 to 2. Thus, for example N =5 we can define the following condition:

$$P_f < 0{,}01 \times 5^{-2} \qquad (35)$$

which correspond with the reliability index for 1-year lifetime $\beta_{t,1}$= 3,5, and for 50 - years lifetime $\beta_{t,50}$ =2,3.

In case of the road barrier, we should adapt the theory above with some constraints represent that structure means the road barrier in unit length e.g., 1000m and in every accidental situation at least one person is present.

4 Crash phenomena

The crash event can be described like the situation when two objects get in contact/ impact together, while at least one of them has an impact velocity. The significant deformation or stress exceeds the yield/ ultimate strength is admitted. The time of the impact is very short (milliseconds), therefore material strain rate effect should be considered as well.

Since the road barrier crash is a typical crash event, there are some specific features compare to the other examples (e.g., car to car crash, car to rigid obstacle or quasi-static structural analysis)

- Road barrier crash has a relatively long time of mutual vehicle- obstacle contact (usually more than 1 second). Comparing to car to car /object crash, which takes app. 0,2s. Typical feature of the road barrier crash is two individual contact patches – mainly in case of the HGV or LGV impact. Initial contact occurs in the front of the vehicle cab then second with the rear part or trailer or vehicle chassis.
- The significant parts of the structure or vehicle is likely scraped out during the crash.
- Overall conditions and unpredictable variables of the crash could significantly influence the crash behaviour and resistance. Typical examples are e.g., the soil condition where the post is rammed, tyre puncture phenomena, road surface conditions etc.

Crash event description

Description of the crash event is a complex problem. Traditional analytical methods are very limited in this case. Many of variables needs to be omitted or simplified, in order to get a result.

The most powerful mathematical tool to describe the crash event in complex is the numerical simulations. Most suitable and complex methods are based on the non-linear dynamic explicit code. The modelling approach utilizing the numerical code is described in section 4. This approach becomes popular in the design and testing of the structures and many different products.

Also, CEN committee TC226/ WG1 react on this trend. The document *EN 16303:2020 Road restraint systems - Validation and verification process for the use of virtual testing in crash testing against roadside device* defines a list of indications to ensure the competences of an expert/organization in the domain of virtual testing.

Despite improvement of CAE engineering and numerical simulations methods, the certification and homologation based on numerical methods only is not anticipated in a near future. The goal of the modern approach is to reduce number of the physical tests and substitute them by numerical simulations. Such an approach would significantly reduce costs for any road safety system development.

At present for new type of road barrier approval, the crash test is the only one recognized. The results of theoretical simulations compared with crash tests, may be used for test validation. Correct simulations are further applied to prove the design modification of barriers, e.g., improvement of details, changes in material and restraining level. Modification should be understood as specific design changes of the VRS defined in EN1317-5. It is divided into three groups depending on the importance of design change. To accept the simulation as a relevant testing method, acc. to the “modification group B” definition in EN 1317-5 the design changes of the road barrier cannot significantly differ from the experimentally tested original barrier.

5 Modelling of the accidental impact event

5.1 Analytical model of the accidental impact load

Main principles of the analytical modelling process are presented above. The existing analytical models [3] [6] [17] [15] suffer from the lack of theoretical information as well as representative real test feedback. Therefore, the calibration of the analytical models is highly required. However, its application seems to be very limited in reality.

The existing models does not cover the deformation characteristics of the individual parts such a vehicle, road barrier, obstacle etc. It is obvious that traditional analytical models are not capable to predict the real test results in detail. Despite of it, is appropriate to extend existing analytical models.

5.2 Definition of the ultimate limit state for road barriers

Ultimate limit state function (ULS) is a key factor for further analytical modelling of the impact accidental situation. Definition of the Ultimate limit state for typical civil engineering structures is almost clear. Girders and other beams have maximal payload to withstand. The anchor has maximal force which can be transferred before it cracks.

Fig. 16: Example of ULS exceeding for girders (left) and anchors (right)

ULS for road barriers and similar systems is not easy to define. Unfortunately, exact definition of the road barriers maximum pay load does not exist. The problem is more complex. First, the road barrier must withstand the design load imposed by accidental impact. It means that road barrier with restraint level of:

- H1 have to withstand the impact of the HGV 10t with impact velocity 70kmph and impact angle 15 deg. – see tab.2 or EN 1317-2.
- H2 have to withstand the impact of the 13t bus with impact velocity 70kmph and impact angle 20 deg.
- H3 have to withstand the impact of the HGV 16t with impact velocity 80kmph and impact angle 20 deg. etc.

Moreover, it must be considered that much harder impact occurs in real operation. However, the road barrier structure which resists most of the potential impacts cannot be done. Contrary, all road barrier structures must provide sufficient protection to hard impact for occupants inside a small passenger's car. Assessment utilizes standard common criteria defined in [7], see section *2.3, Standard EN1317:*

- Acceleration severity index ASI
- Theoretical Head Impact Velocity (THIV index)
- Occupant´s injury risk criteria (VCDI index)

Fig. 17: Small vehicle deformation after road barrier crash test

Limiting conditions to define the Ultimate limit state for road barriers is reasonably summarized in one statement. *“Ultimate limit state of the road barrier occurs if the barrier (longitudinal element) fails, or the barrier lost its protective function”*

It means particularly:

- Road barrier must be stiff enough to withstand the heavy impact imposed by truck, bus or another heavy vehicle, and
- must be soft enough to protect the occupants in the light (passengers) vehicles against the crash consequences

Therefore at least two threshold values or scenarios for Ultimate limit state should be defined. It means that road barriers play a different role for different type of the impact. Both scenarios have different criteria to assess.

- First scenario: Light vehicle impact: There are two main criteria to assess the ULS
    - Extreme or insufficient road barrier deformation criteria
    - Occupants hazard criteria (hard acceleration measured on the vehicle body). Occupant’s hazard criteria are hard to assess analytically. Thanks to numerical simulation they could be analysed.
- Second scenario: Heavy vehicle impact:
  Three main criteria would be considered to assess the ULS in case of HGV, LGV or bus impact:
    - Failure of longitudinal elements or loss of stability of pillars (plastic joints)
        - Maximal stress exceeds the ultimate strength of used material
        - Maximal strain exceeds the material limit, in plastic joint zone or guardrail.
    - Criteria for overcoming the barrier/ overturning the vehicle
        - Evaluation of the vehicle movement from numerical simulation.
    - Extreme deformation criteria
        - Evaluation of maximal deformation for post in impact zone. This criterion could be assessed by both analytical and numerical simulation.

Note: It is obvious that the complete road barrier ULS assessment is hard to analyse using the analytical approach only. Complex numerical simulation is crucial in criteria assessment e.g., the *occupants hazard criteria, vehicle overturning/overcoming assessment and vehicle trajectory after impact assessment.*

3.3 Model uncertainties

Model uncertainty, with respects to [6], represents the basic variable related to the accuracy of physical or statistical model. Basic variables in limit state function [16] can be influenced by many physical or informative uncertainties.

Complementary information provides JCSS [18] and [19] [20] [16]. It is advisable to consider in the limit state function (6) the model uncertainties for the load effect Θ_E as well as for the structural resistance Θ_R, so it can be written:

$$Z(r,e) = \Theta_R R - \Theta_E E \quad (36)$$

Load effects uncertainty Θ_E is the combination of uncertainties included in:

- Impact angle
- Mass of the vehicle
- Impact velocity
- COG position and inertia

Structural resistance uncertainties Θ_R arises from the lack of the information, modelling approach or low number of tests samples. They are classified as an informative (or epistemic) uncertainty.

- Modelling approach uncertainty
    - Material mechanical properties incl. dynamic load effect and climate effect
    - System anchorage properties e.g., soil or bridge parapet properties
    - Impact vehicle structural uncertainty. Even if this uncertainty belongs rather to load effect Θ_E.
- Workmanship and installation quality control.

Third main group denotes the methodology uncertainties. These arise from crash event definition and its general simplification and measuring of the parts and installation dimensions. Therefore, we can assume the following groups:

- Geometrical uncertainty (parts dimensions and installation dimensions)
- Measuring uncertainty arising from the methodology of the measuring the geometrical dimensions.
- Crash event simplification due to the used methodology.

3.4 Model uncertainties referring to the physical crash

One of the main thesis objectives is to define and precise the model uncertainties referring to the physical crash tests. The model uncertainties are defined with respect to the crash test phenomena, the test sample behaviour and specific features of the test preparation. The typical statistical distribution of the values e.g. material properties, measurement precision or random effects are also considered. However, it is not the main aim of the thesis. The model uncertainties considered in the thesis can be divided into four main groups:

- Load effect / Structure resistance uncertainties
    - **Vehicle mass - acc. to limit defined in EN 1317**
    - **Impact angle - acc. to limit defined in EN 1317**
    - **Impact velocity - acc. to limit defined in EN 1317**
    - Track condition - dry, moisture, wet, snow, respectively temperature
    - **Tyre puncture effect Yes/ No**
    - Vehicle COG position
    - Vehicle frontal part shape
    - **Mechanical properties of the soil** or bridge parapet
- Geometrical uncertainty (parts dimensions and installation dimensions)
    - Main parts dimension (posts, guardrail, bolts)

    - Bridge curb rail dimension
- Measuring uncertainty arising from the methodology of the dimension measurement
- Installation uncertainty arising from different installation methods and work practice.
    - Post pitch
    - Post ramming depth (in case of the soil installation)
    - Road barrier end installation
    - Guardrail height and connection to the post
    - Bolt connections (torque, bolt grade etc.)

The objective of this study is to analyse influence of variable input conditions on the crash test results. Numerical simulation is utilized for sensitivity analysis of model uncertainties. **Highlighted** items were chosen to be explored further in sensitivity analysis. The results of the analysis are shown in section *9" Sensitivity analysis of the model uncertainties"*.

6 Numerical simulation of the road barrier accidental situation

6.1 Finite element analysis

Numerical methods as a tool in Computational Mechanics has been used from early sixties. Numerical – based methods have been originally applied in the automotive and aeronautic industry for many years. The development and the approval of aircrafts and new vehicles within an acceptable timeframe and budget are not possible anymore without simulations support.

Due to an increasing number of requirements for design, costs, and safety it is unlikely that engineers fulfil all requirements at the first attempt. That is why CAE engineers predict the systems safety performance with Finite-Element simulation models.

Implementation of Computational Mechanics and other mathematical methods in the field of roadside safety has increased in the last decade [21] [22] [23]. Certification process via results of the computational simulation of the real crash tests is under discussion at European level. Today, it is forbidden to substitute experimental tests with theoretical analyses only (numerical simulations as well). However, analyses may be used for the designing of barrier modifications. In the meantime, expectations on model outputs are increasingly precise and, nowadays, one expects the model to be predictive. The sufficient level of the model predictability cannot be achieved without a parametric approach which takes into accounts many parameters which are mostly of the stochastic variations such e.g., mechanical properties, impact conditions, modelling approach and range of the simulation. The accuracy of a modelling approach is based on the knowledge of a reasonable range of variation for each basic variable [21].

There are a wide range of approaches which they can be used to create a complex and detailed model of the RRS accidental situations. Numerical- based methods can be realized in many of different commercial sw. products and they can be basically divided in next three groups, depending on the calculation methods presented here in order of their complexity. Obviously, all approaches have their pros and contras. Main simulation approaches are shown below:

- Static analysis of the RRS loaded by equivalent static force.
- Multi body approach of the RRS crash with non-deformable parts.
- Finite element modelling of the RRS full scale crash.

Static analysis

In common case, for the purpose of structural design the impact is represented by an equivalent static force giving the equivalent action effects in the structure. The static analysis based on the equivalent horizontal force is the simplest approach with very good operability. All these methods are based on the implicit code. Therefore, the calculation does not take into account the time component. Results describe an answer of the structure to applied load in one static equilibrium time point.

This method represents a simple tool to perform the initial model of the RRS crash.
However, the model suffers from significant constraints, e.g.:

- Loading effect of the inertia mass cannot be included (time invariant analysis).
- Impact is represented by pure single loading effect (mainly the horizontal force).
- Soil conditions are hardly to be captured.
- Strain rate effect cannot be captured.
- Occupant’s risk, vehicle redirect and some of the quantitative criteria cannot be evaluated.

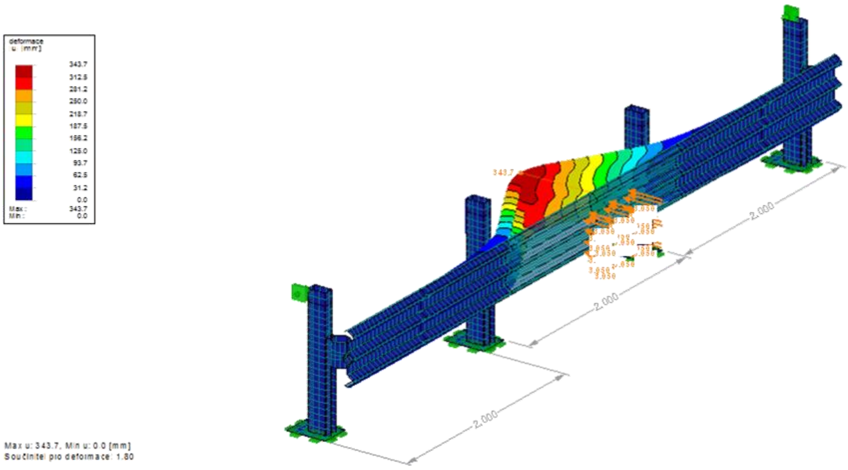


Fig. 18: Road barrier FE model – Static analysis in RFEM environment

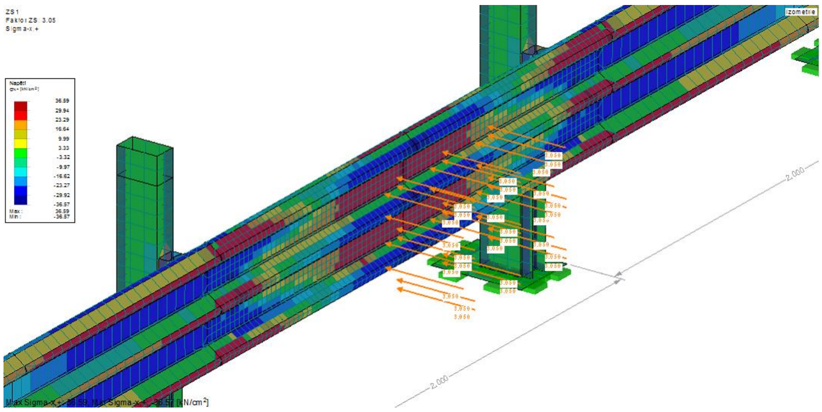


Fig. 19: Road barrier FE model – Deflection evaluation in RFEM

Simplification of the crash conditions to pure force in perpendicular direction to the RRS is not sufficient for detailed analysis. Computational simulations show that contact force components (especially in vehicle movement direction) and other impact features play a significant role in the RRS loading.

Multi body RRS crash simulation

More comprehensive solution is multibody approach. In that case some parts are realized by Rigid Bodies (e.g. Cars, system end etc.) These objects can get in contact with initial conditions (velocity, mass etc.) Multi body simulation represents a compromise between modelling demands and results validity. However, multibody approach suffers from significant constraints e.g.:

- No vehicle deformation
- Some of the parameters cannot be assessed, i.e.:
    - ASI (Impact severity index)
    - VCDI (Vehicle cockpit deformation index)
    - THIV (Theoretical head impact velocity)
- Interaction vehicle- RRS is limited due to the rigid impact model.

- Outcome vehicle track is significantly influenced by used approach.

Contrary, approach is capable to provide results in a short time. Finally, the multi-body approach is reasonable to be used in concept design phase to provide the many rough results in very short time. Obviously, multibody approach is not suitable for detailed impact analysis. Thanks to available computation power and sw. tools in recent years the multibody approach was fully substituted by complex FEA analysis.

Non- linear dynamic Finite-Element Analysis

The Finite Element Method (hereinafter referred to "FEM or FEA") is worldwide known and used method in many industries including civil engineering, machinery, and the automotive industry. In the context of this work, the numerical simulations and especially the explicit non-linear dynamic method are shown as modern powerful tools to analyse the structural behaviour under the accidental or other different dynamic load.

FEA is approximate tools, using the numerical system of differential equations to describe the real-world phenomena. For the simulation of high -speed, nonlinear plastic deformation event e.g. crash tests the suitable dynamic mechanical analyses must be conducted. Explicit Finite-Element code is appropriate to analyse the crash events [23].

However, nonlinear explicit analysis is strongly sensitive to the input data, modelling technique and operator skills. Improper use may lead to unexpected or unreal outputs. Therefore, the numerical simulation of the crash event will be further described in detail incl, typical features of modelling approach, validation procedure etc.

All analysis presented here in this work and its outputs has been done in explicit non-linear dynamic environment VPS Solution, known as Pam Crash, developed by ESI group France.

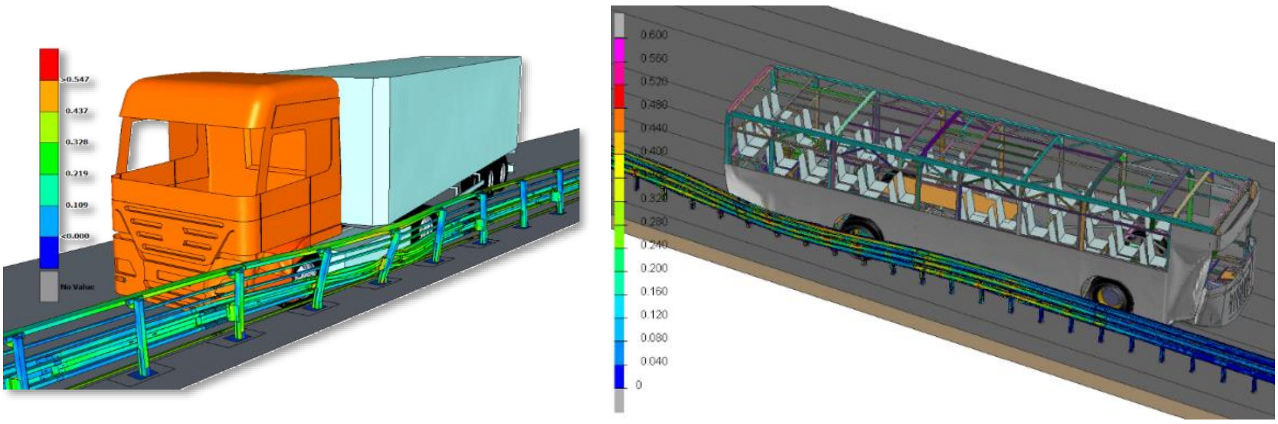


Fig. 20:Finite-Element Analysis of the road barrier crash test (Test TB 81and TB51), illustration figure

RRS crash test simulations using FEM is usually a strongly nonlinear dynamic task. The task is solved using explicit analysis. Explicit code allows to analyse the system response in time with defined minimal time step Δt between two solution steps. Solution of the differential equation matrix in defined time moment provides the initial conditions for solution in next time step $(+\Delta t)$. Therefore, the inertial forces are integral part of the solution process. This feature is essential for explicit code. Theory of the numerical methods based on the explicit/implicit code exceeds the thesis framework.

FEA allows to perform a fully detailed model and assess the road barrier behaviour as well as the vehicle during the crash event. Furthermore, it is possible to gain a complex overview of outcomes related to the structural deflection, stress distribution and energy balance. However, this approach needs a demanding computation performance and capacity. Due to the different requirements to modelling in various sw., it is advisable to know the capabilities of the used software.

Non-linear dynamic software PAM-CRASH suitable for the computation of large plastic deformations step-by step beyond the yield strength of the material is used for all crash simulations presented in this study.

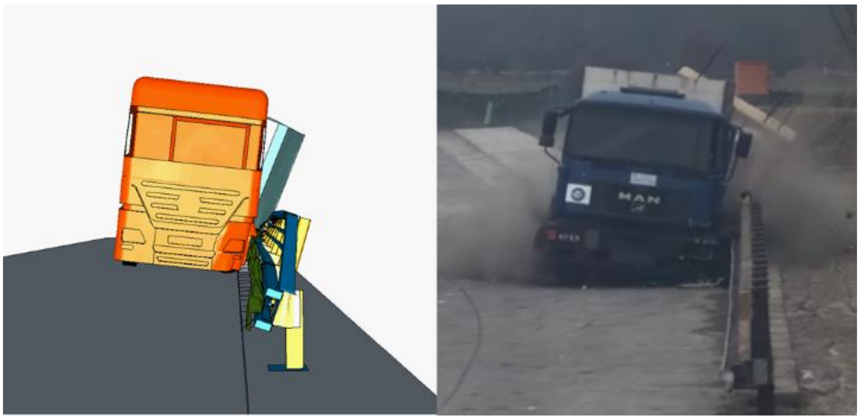


Fig. 21: Comparison of the computer simulation and real crash test

6.2 FE simulation of the crash event

The simulation of the road barrier crash tests is a complex problem depending on many input parameters. Modelling the impact event using nonlinear dynamic simulations has limiting conditions. The wide range of the simulations indicates several fundamental problems that need to be considered.

- Contact tasks are main parameters for simulation tuning. Within the high-speed crash event simulations, a problem with the stability of the numerical calculations and capturing elements are crucial. These problems lead to the complete impairment of results. This issue is also magnified by the requirement for a lengthy time simulation (more than app. 500 ms). Therefore, it is necessary to avoid the accumulation of numerical errors by using of high precision solutions or similar features.
- Vehicle models should be validated to ensure a real deformation of the structure. This demand is not so strict for commercial vehicles modelling (buses, HGV and LGV).
- The material characteristics should be validated through the real experiments. Highly advisable is to define the material behaviour above the yield strength as well as at high-speed deformation.
- The size of the curb rail and road barrier offset. Currently there is no given a harmonized height of the bridge parapet for a physical test in the EU states. Thus, it is necessary to prepare computational simulation within the parameters of the testing lab.
- The friction coefficient between the wheel and road. The best is to use the revolute wheels and tyres in the crash simulation.

The expectation from Non-linear dynamic FEA simulation of the crash event could be summarized in several points:

Pros:

- Structural system behaviour under the impact conditions.
- To analyse the qualitative evaluation criteria.
- To analyse all quantitative evaluation criteria.
- Expected biomechanical load of the occupants (in relevant tests).
- Anchorage influence analysis.
- Analysis of the outcome area and vehicle movement after impact.

Contrary, there are some features which are hardly captured:

- Prediction and analysis of the longitudinal members failure.
- Tyre puncture prediction during the crash event – see later.
- Analysis of the crushing effect in case of the concrete road barriers.
- Calculation time. Particularly when termination time of the simulation exceeds 1000ms.
- Significant amount of the resulting data. Output files are usually in range of gigabytes.

6.3 Specific features of the road barrier FE model

For a different type of the road barriers, the appropriate approach of modelling should be applied. Main decision parameters are the material of the barrier (steel, concrete, and others) and anchorage type (bridge parapet, soil and others).

Simulation model must involve significant length of the road barrier (up to 100 m) to reproduce boundary conditions and interaction between the vehicle and the barrier, and in the barrier itself.

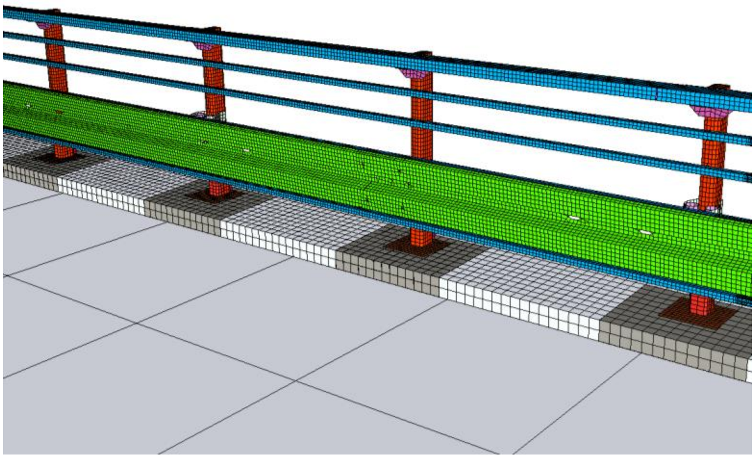


Fig. 22: FE model of the road barrier installed on the bridge parapet –mesh example in impact zone (nominal element length 10mm)

The time step in the FEM is determined from the smallest element, so it is important to have a uniform mesh with enough geometric and numerical accuracy. Elements with coarse net have a fast time step but may not sufficiently represent the shape of the object. The most significant parts of the model should be modelled with a sufficiently fine mesh size.

For the initial verification of the road barriers, the bilinear elastic-plastic material model can also be used, further completed of real stress-strain diagram from the material tests.

Elasto-plastic material models are used for steel barriers. Steel is typical by hardening effect when yield strength is exceeding. This is an essential characteristic for the described tasks. This reinforcement effect can be modelled according to the material law by Krupkowski and Swift:

$$\sigma = k \cdot \left(\varepsilon_0 + \varepsilon_p\right)^n, were\ \varepsilon_0 = \sqrt[n]{\frac{\sigma_y}{k}} \qquad (37)$$

where *k* and *n* are the material constants determined by the tests.

Engineering stress-strain diagram for different loading speed are shown in Fig. 23. It represents typical steel material used for longitudinal beam of the road barrier. We can obtain stress-strain curve from the tensile test and directly it uses in the simulation material model.

Crash event is a high-speed event, therefore strain rate effect (material resistance vs. loading speed dependency) should be considered in material model, although these data is difficult to gain.

Material model based on the real stress- strain curve should be defined for main longitudinal members of the road barrier model.

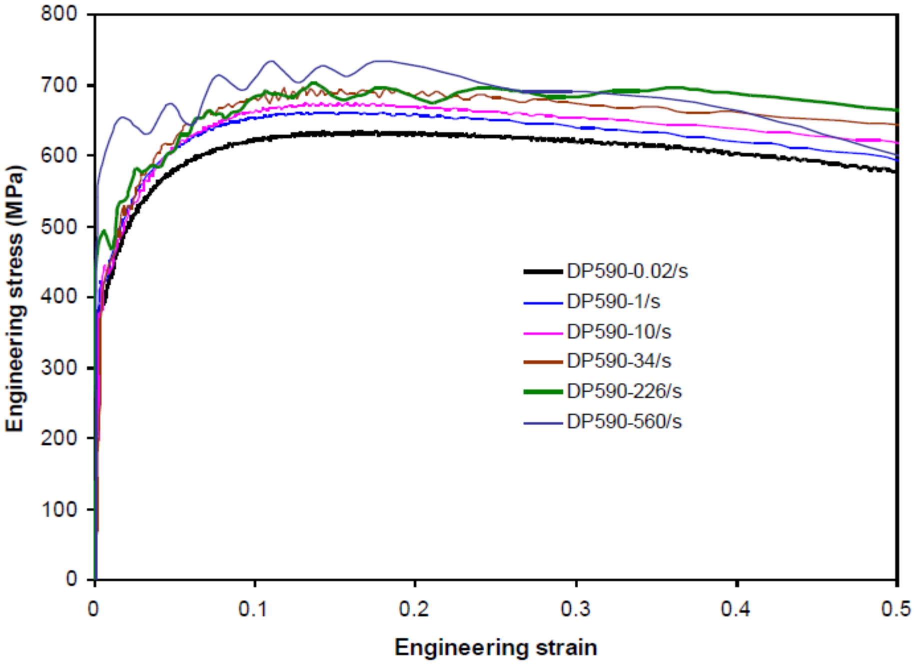


Fig. 23: Engineering stress- strain incl. strain rate effect, example of DP 590 steel

The situation is much more complicated in case of monolithic concrete road barriers. More details can be found in [21].

Road barrier anchorage points

The fixation of the posts in the ground may correspond with the test conditions. It is necessary to distinguish whether the barrier is fixed into the bridge curb using anchorage bolts, or posts are purely rammed into the soil. In the first case, the anchor bolts can be modelled as other screw connections on the barrier.

There are many approaches to represent the anchorage of the posts rammed into the soil, e.g. by meaning of springs with different stiffness over the depth. Stiffness is based on the soil characteristics, obtained from the detailed geotechnical survey. Stiffness must be specified at least for three posts determined over the depth of the barrier pillar. This stiffness can be simply defined by the boundary conditions. In most cases will be applied for the springs $k_3 > k_2 > k_1$.

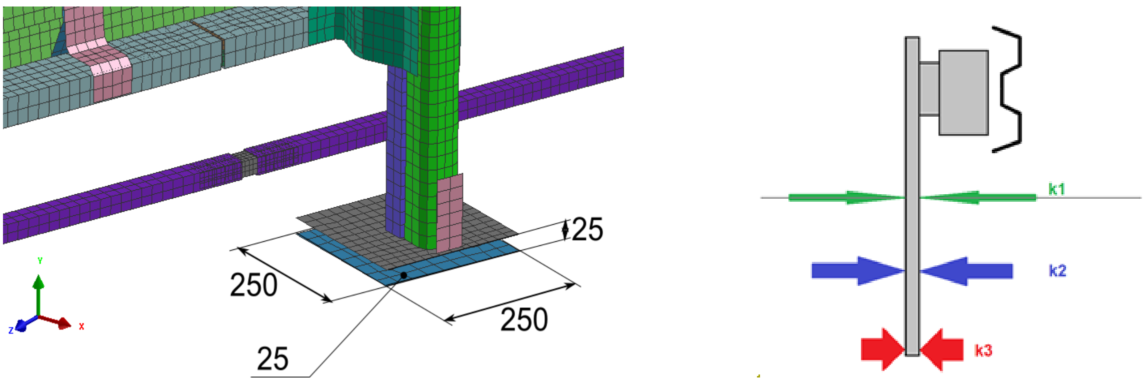


Fig. 24:Detail of two different type of road barrier anchorage (bridge parapet – post rammed in soil)

FE model of the road barrier support and anchorage needs to be tuned up using real values of the soil properties. Fortunately, acc. to the latest update of EN1317, the soil characteristics should be attached to test report from real road barrier crash test.

In case that no information is available the pure post anchorage below the road level can provide a sufficient match with the real test as it is shown in Fig. 25. Partial investigation shows if the post fixed app 200 -250 mm under the road provides the good match in comparison the behaviour in the real tests.

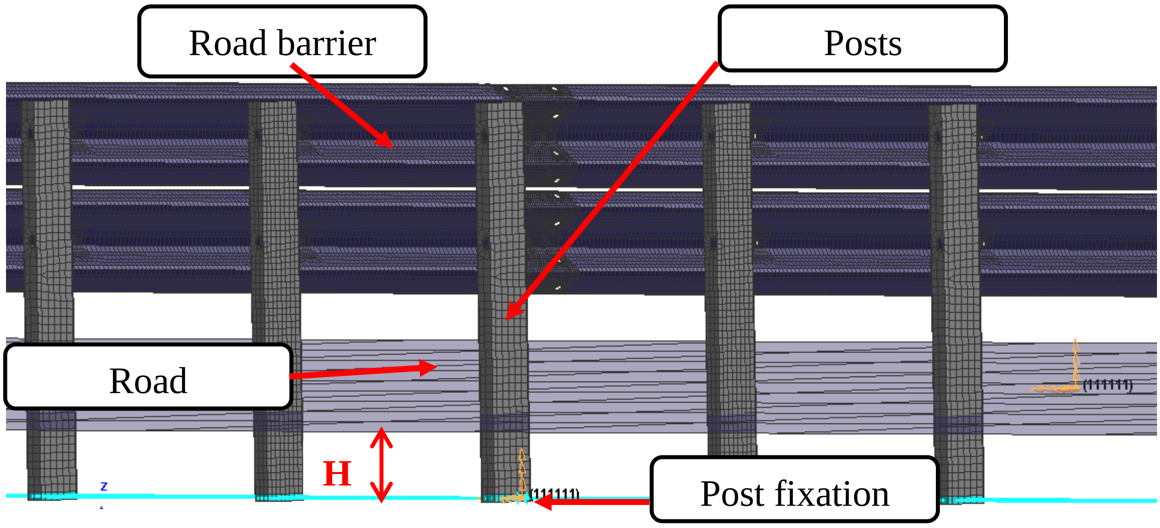


Fig. 25:Road barrier posts anchorage

Soil properties

Soil properties can be measured by oedometric test. Soil characteristics can be measured in situ as a main advantage of this approach. The outdoor oedometric test consists of pushing the plate into the soil with the results in a stress-push diagram. The load, respectively plate pushing continues in several cycles. The resulting soil characteristics are determined for different load intervals. These characteristics can be included in the road barrier simulation model, which leads to further refinement of the simulation model, if necessary.

Detailed soil modelling is more demanding in term of the model complexity, input data as well as computation time. Therefore, it could be recommended in specific cases, where standard approach does not provide reasonable results.

Note:
Output gain from the oedometric test is usually the soil compression in one direction (one axis). Soil mechanical properties in numerical simulation model will be applied in all axes, which represents typical isotropic material. Despite this the results of the simulations represent well the real soil behaviour.

Concrete Road barriers

Road barriers made of the concrete mono block represent the specific group of the RRS. Therefore, the FE modelling approach has some constraint and certain features must be accepted. Main differences of concrete road barriers behaviour under the impact as well as modelling approach are described in next article.

Deflection during the test

Deflection of the existing concrete road barriers has a different mechanism in comparison with the steel road barriers. While steel barriers have in crash tend to bend in post, the concrete barriers deflection is more like the chain as is shown in Fig. 26. Final deflection of the system is highly influenced by the shape of the gap between the mono-blocks as well as the structural behaviour of the connection points. Possible contact patch in the corners has also affect as shown in Fig. 26.

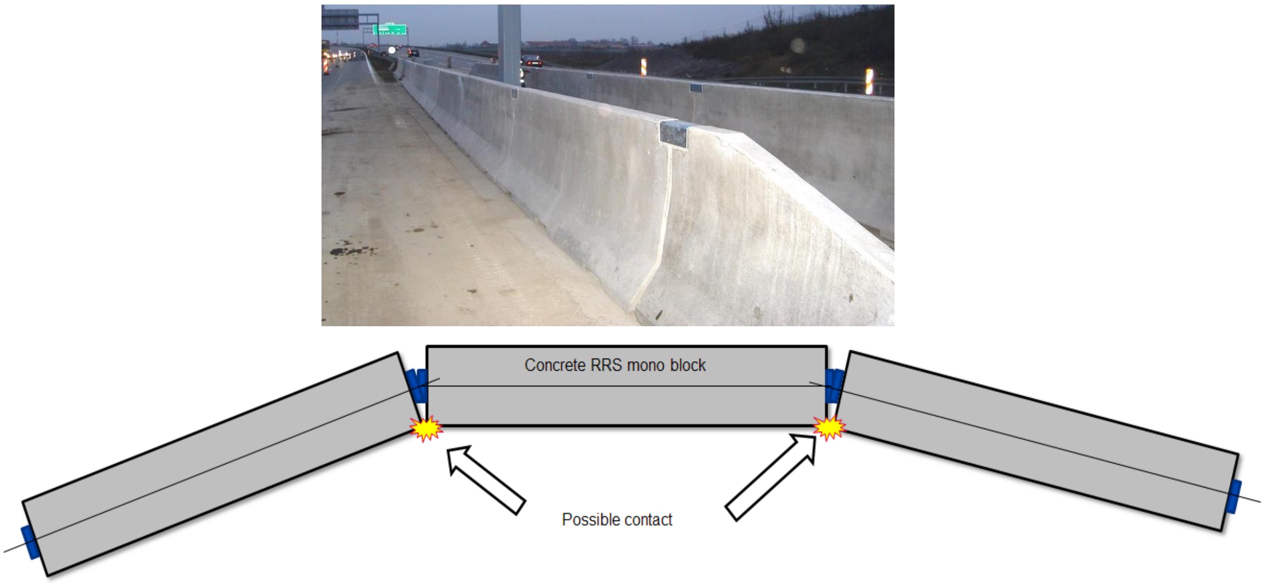


Fig. 26:Example of typical concrete road barriers and its deflection mechanism

Concrete material model

Crucial problem of this simulation is the concrete material model used for the monolithic block of the system. Question is how to define the significantly different mechanical properties in tension and compression. Unfortunately, the suitable material model is not available for the nonlinear FEA sw. tools used in crash analysis (e.g., Pam Crash, LS Dyna, Abaqus, ANSYS etc.).

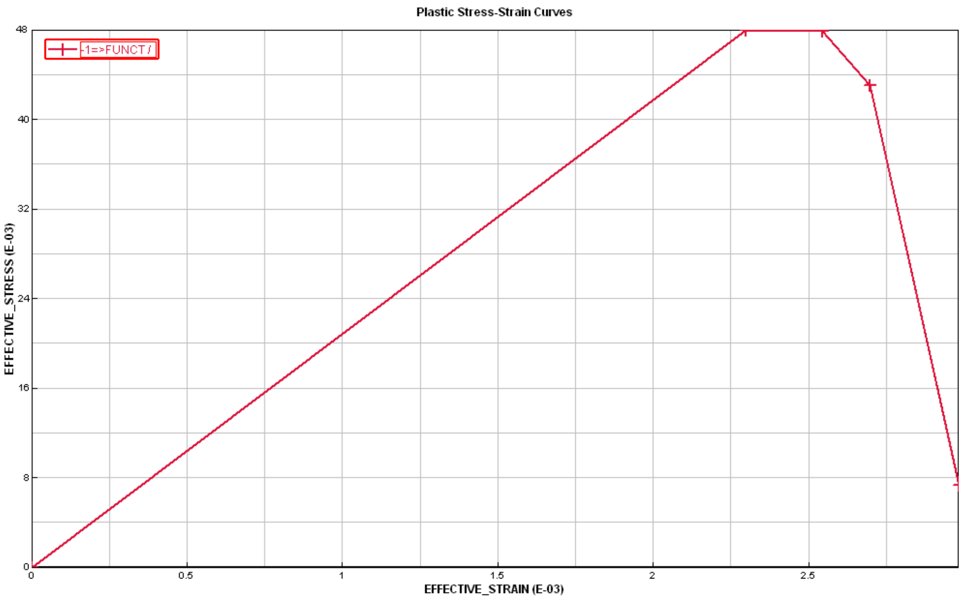


Fig. 27: Simplified stress-strain curve for C40/50 concrete material in compression

Pure elasto-plastic material model should be partially used to describe the concrete material, see the Fig. 27. However, utilization seems to be very limited in this case. A modern module material model has potential to improve the concrete material model in crash analysis.

Concrete- steel internal reinforcement

Finally, the problem is reduced to mutual connection and interaction between the concrete material and internal steel reinforcement? In common cases, the deformation of the concrete mono-blocks is not relevant. Therefore, modelling of the system could be simplified to the rigid bodies only. This feature is typical behaviour of New Jersey concrete road barriers, where its restraint performance is given by its mass and geometry.

Mutual interaction and mechanical connection between the concrete and steel reinforcement needs to be engaged if deformation of the system is significant.

6.4 FE model of the impact vehicles

Standard [7] defines the basic parameters of cars to be used in real crash tests, such as dimensions, weight, and CoG position. However, the results of the real crash test may vary a lot according to the used type of the testing vehicle. Type of the vehicle then become decisive factor in the test where the road barrier is close to the limit.

Since testing institution uses different vehicles, then the compatibility of the results cannot be fully guaranteed. This may be even more significant when older vehicles are used for crash tests. These vehicles are not divided into individual impact zones, while their structure could be considerably damaged by corrosion or improper repair.

FE model of the passenger car

In order to get a reasonable result, all vehicle models should be complex and in detail. Further, the kinematical as well as crash model response may be validated with the real data. Validation procedure is focused to assess the vehicle crash performance comparing to standard passive safety crash tests, e.g. acc. to EuroNCAP or ECE regulation.

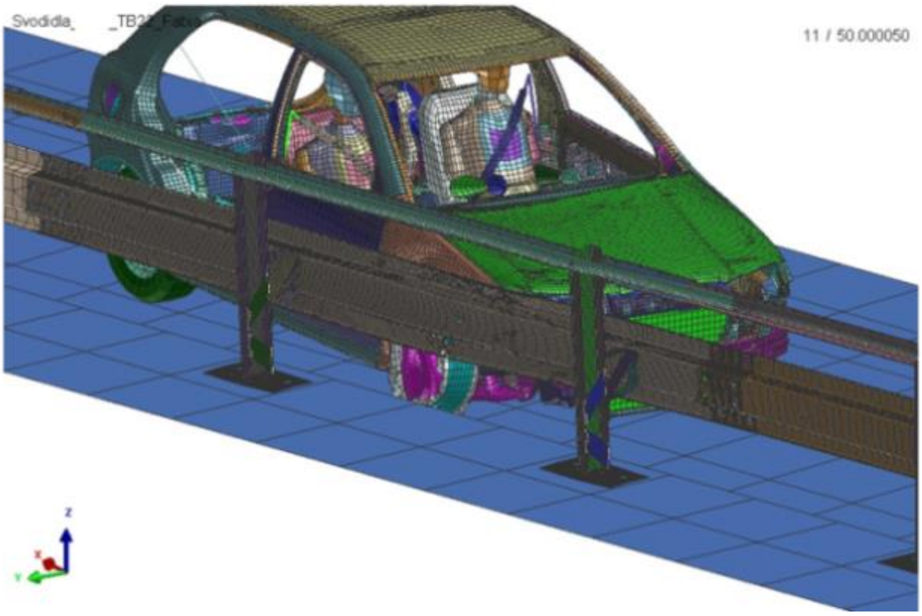


Fig. 28: FE model of the small passenger car

FE model of the bus and heavy goods vehicles

In the light of available information, the testing institution in the Czech Republic uses an older type of the Karosa bus (1980s and 1990s) for the standard crash test. It is a typical representative of the intercity bus (category MII) with a length of 12 m. The shape and method of construction of commercial vehicles (buses, HGV and LGV), does not have a significant effect on road barrier crash simulation results. Contrary, the frontal part shaping has significant effect to the crash behaviour. Therefore, this part of the model needs to be modified according to the real vehicle, as is shown in Fig. 29 .

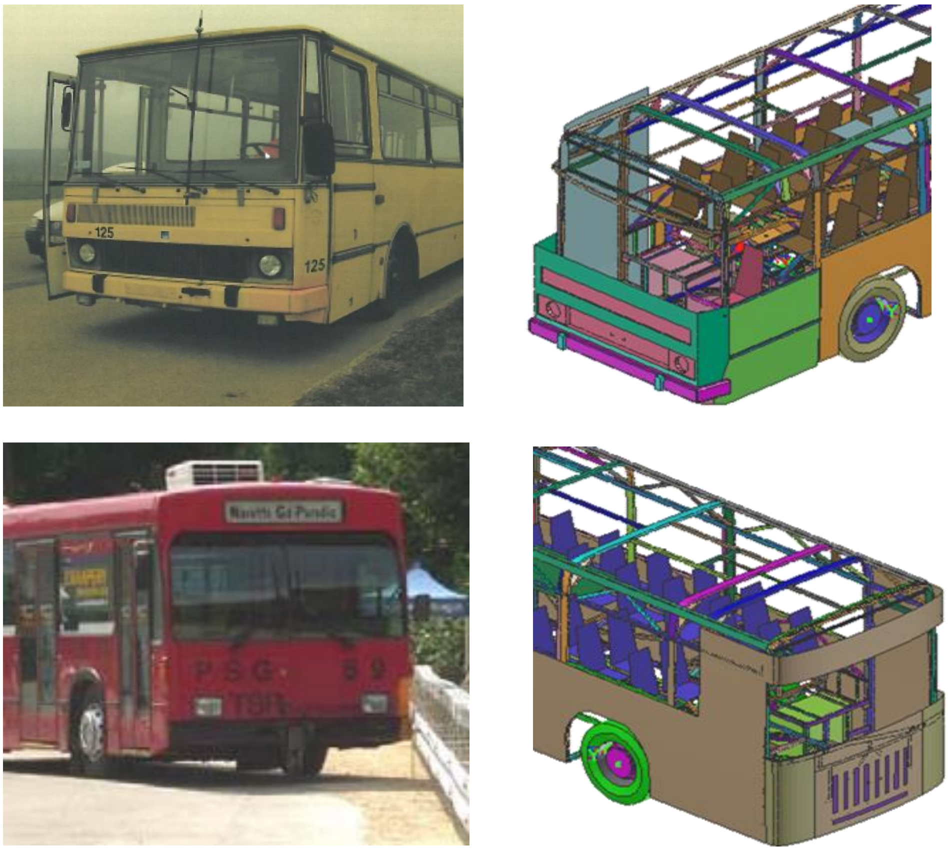


Fig. 29:Bus FE model adaptation to real test vehicle

7 Experimental data from the road barrier crash tests

The experimental data from the physical tests is the essential input base for further thesis work. Within a frame of this work the physical data from approval road barrier crash tests has been gathered. All information from the tests is summarized in database form.

Complete data package in the database has been measured by accredited testing laboratory. It should be noted that database contains secret data and therefore it is strictly anonymous with no reference to the road barrier manufactures. The content of the database is unique and similar information source has never been published.

Some of the test samples are completed by detailed technical report. Therefore, the modelling of the crash event could be more precise e.g., impact conditions road barrier modelling and impact vehicle features. Obviously, these reports cannot be fully published, due to its secret content.

The database contains more than 50 crash test samples. Test samples are divided into three main groups:

- Steel road barriers in ground or soil
- Steel road barriers on bridge parapet
- Concrete road barriers

Database information referring to the particular road barrier is divided into subgroups:

- Test Description - means the overall information referring to actual test.
- Impact vehicle parameters – means the initial conditions of the vehicle parameters e.g., the mass, dimensions, COG position, impact velocity, impact angle, impact position etc.
- Test results – means the evaluation of the test result according to the EN 1317 e.g., Dynamic deflection *D*, Working width *W*, Vehicle intrusion *VI* and its normalised values. In case of the small car tests the parameters of the occupant's impact severity are displayed.
- Graph outputs description – means the description of the graph values (peak@time), if relevant.
- Test sample (Road barrier) description – means the general information about the road barrier structure and design referring to the test e.g., material, overall dimension, Guardrail type, installation length etc.

For overview of the experimental data see *Appendix 2- Road barrier test EN1317 Database*. Only selected crash test samples are displayed.

8 Simulation of the selected crash test scenarios

Total of 8 physical tests from database were selected to validate the simulation and modelling approach in thesis. These tests cover typical variants of the road barrier crash tests. As mentioned in introduction the physical tests utilized in the thesis are aimed to the steel barriers only, installed on the bridge or in the soil.

The following criteria were applied to select the proper physical test to simulate:

- Data availability (maximal). Complete technical report from the physical test was preferred.
- Heavy vehicle impact. Crash tests with light and passenger car were supressed.
- Road barrier installed either on the bridge parapet or into the soil.
- Different road barrier manufacturers mean the different structures.

Selection of suitable candidates beyond these criteria was essentially random. The order and numbering of the case studies depends on the database ordering and does not reflect any other features (importance, type of the tests, results etc.). All case studies are summarized in Tab. 8.

Tab. 8:Case studies list for modelling approach validation

Case study no.:	Test identification	Post anchorage	Road barrier design	Information source	Note
1	TB 51	Ground	Steel, Post C, Guard rail 2x A	Test Report	see thesis
2	TB 11	Ground	Steel, Post C, Guard rail B	Test Report	see thesis
3	TB 51	Ground	Steel, Post C, Guard rail A	Test Report	test failed
4	TB 51	Ground	Steel, Post C, Guard rail 2x B	Test Report	see App.1
5	TB 51	Bridge parapet	Steel, Post C, Guard rail B	Test Report	see App.1
6	TB 81	Bridge parapet	Steel, Post C, Guard rail B	No	see App.1
7	TB 81	Bridge parapet	Steel, Post C, Guard rail B	Test Report	see App.1
8	TB 11	Ground	Steel, Post C, Guard rail 2x B	Test Report	see App.1

Please note that main road barrier design features are given in Tab. 8 (e.g main material, post cross section, its pitch and type of the guardrail profile). Test result in case study no.3 was failed, therefore is very important if numerical simulation shows the same results.

There are several types of the guard rails used on most of the road barrier designs from different manufactures. This part is difficult to manufacture therefore there are two main types used in EU countries, simply identified as *Type A* and *Type B*. Both variants are available with two or three waves cross-section profile. Depend on expecting road barrier restraint level.

Two waves guardrails are shown in Fig. 30.

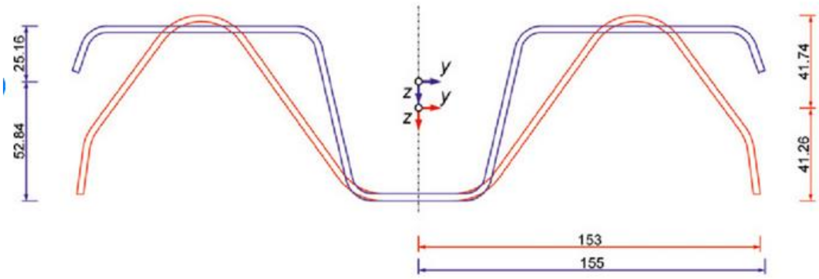


Fig. 30:Main types of the guardrails on the European roads – type A (blue) and type B (red)

Moreover, there is also one guardrail typical for Czech roads, type NH4. The cross-section of NH4 Guard rail is close to the type A, see Fig. 31.

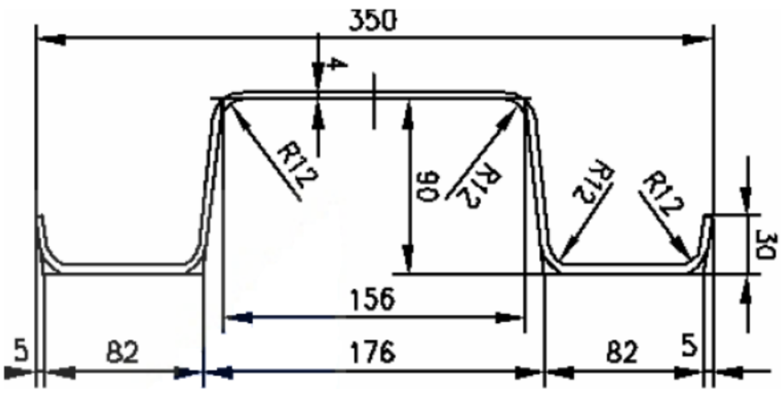


Fig. 31:NH4 guardrail cross section

9 Methodology for FEA verification and results evaluation

The key question of the FEA is "Is the analysis output trustworthy in order to make a decision of the design changes?" Modern FE analyses provide a thorough view on the impact and crash event and its phenomena in detail. Contrary, inadequate simulation results can be easily gained with unprofessional or uninformed modelling approach.

The number of the manufacturers, using FE analysis support for new road barriers design still rising. In the light of this trend would be suitable to note, that any errors in the design increase the risk of crash test fail.

Development costs could be reduced significantly if the number of approval crash tests is minimized. For example, one set of tests of a typical road barrier for H2 restraint level (TB11 and TB51) in the basic configuration costs approx. 55 kEUR. The cost of installation, RRS prototype (min. 100m), and coordination costs excluded. It could be compared with the virtual simulation costs particularly with a few variants of the same structure. Therefore, the careful preparation of the FE model and its verification become essential aspect of road barrier testing.

Verification of the FE model should cover every single aspect of the structure design and its structure response. This process has no fixed rules. Following text represents the author's recommendations based on the certain experience in this field.

1/ Initial conditions: Presumption of the same initial conditions must be fulfilled; therefore, the real condition of the crash test must be reflected in the simulation. Relevant information can be found in Crash Test Technical Report issued by authorized testing laboratory.

- RRS structure must be the same. Any design changes in real test should be reflected in FEA
- Impact velocity corresponds with the real test.
- Impact angle corresponds with the real test.
- Vehicle mass and ballast distribution corresponds with the real test.
- Frontal shape of the vehicle (HGV, LGV and busses) incl. the overall dimensions corresponds with the real test. The front overhang incl. the wheelbase is crucial to analyse the vehicle movement during and after impact.
- Length of the road barrier system corresponds with the real test. The final points of the road barrier system or guardrail must be properly fixed, if shortened in simulation.

2/ Anchorage support comparison:

Finally, the ground anchorage condition could be one of the tuning parameters to achieve a reasonable result.

3/ System response:

The maximal system deformation (corresponds with the quantitative evaluation criteria Working Width *W* and dynamic deflection *D*) are the most important values to validate the virtual model. Maximal deflection of the system during the impact is not easy to be measured in real test. Usually, the high-speed cameras with rough accuracy are used. Thus, the maximal permanent deformation after impact should be comparable. To gain the transparent visual view to the overall deformation of the system, the post deformation graph, see Fig. 33.

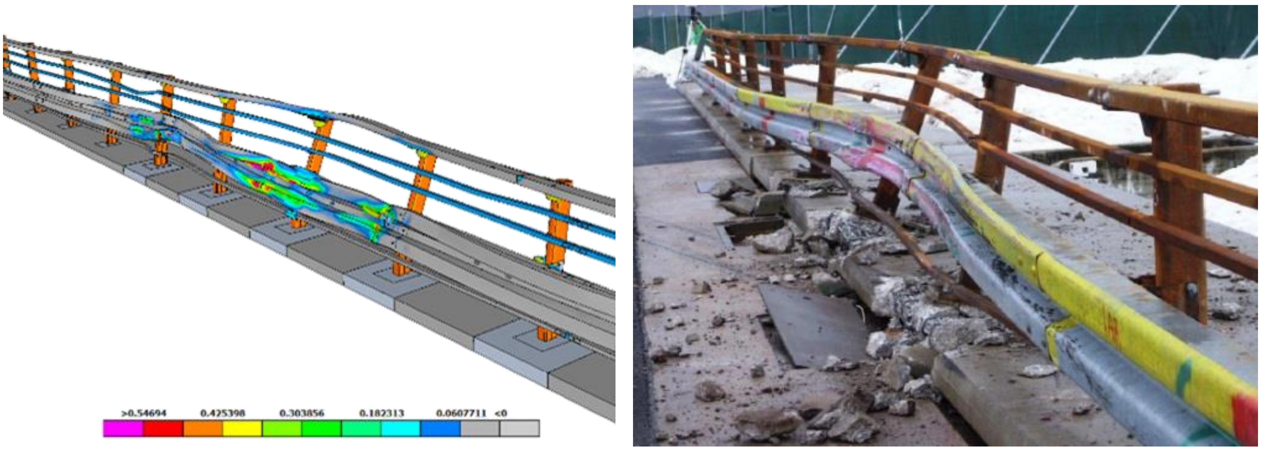


Fig. 32: Comparison of the test results in computer simulation and real crash test

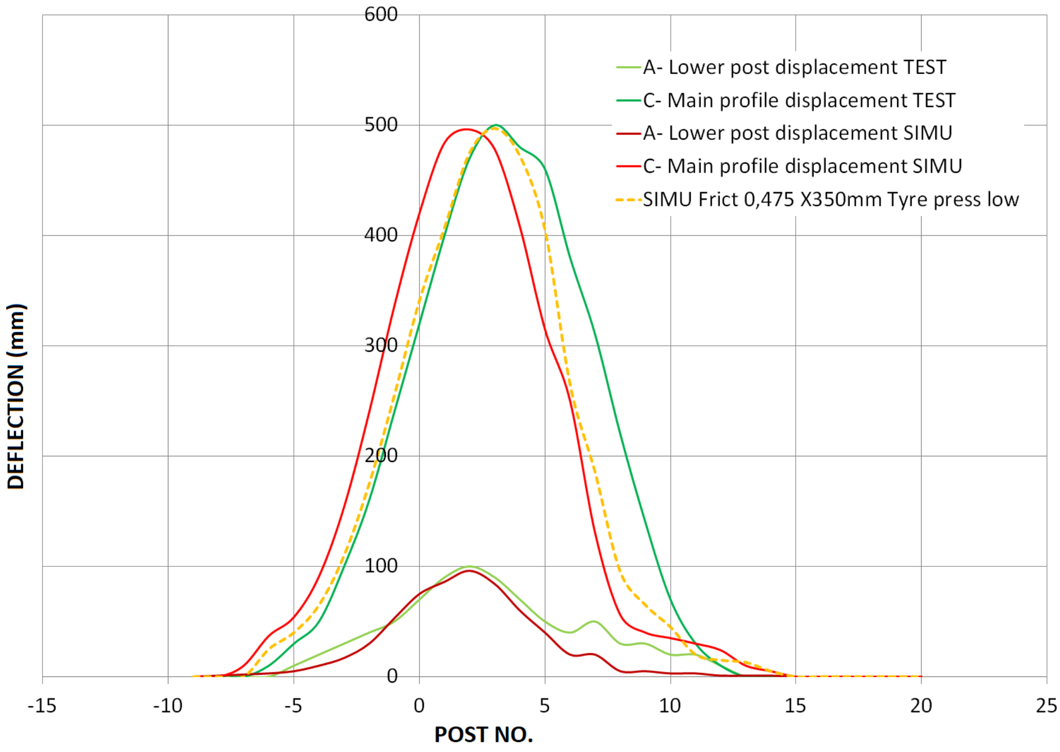


Fig. 33: Illustration of the computer simulation (2 setups) and real crash test results comparison

4/ Vehicle movement assessment after impact:

The goal is to compare the outcome area and vehicle movement direction after the impact. FEA should cover the negligible simulation time in order to describe and assume the vehicle movement. Tyre puncture and discharge effect could affect the final vehicle movement, however not considered in our case studies (in the first instance).

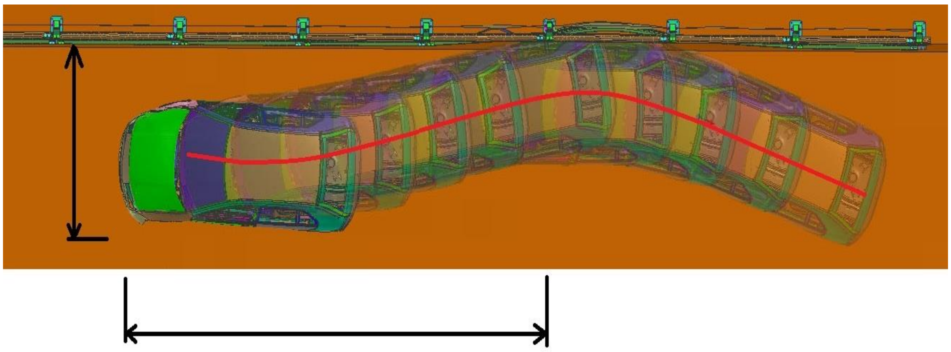


Fig. 34: Analysis of the vehicle movement after impact- FEA

5/ Vehicle deformation:

The deformation of the crashed vehicle part should be comparable with real crash results. Nevertheless, the evaluation of significant damage of the vehicle or its parts, should be complicated. Contribution of the detailed vehicle FE model (in term of the crushable model of the suspension, steering, axis etc.) to the simulation result relevancy is questionable.

Note:
To evaluate the complete trajectory of the vehicle after impact demands long calculation time in simulation (usually more than 1000ms). This could finally lead to some specific numerical problems i.e. computation stability, non-physical component of the energy or accumulation of the computational error.

FEA results evaluation

The advantage of FEA simulation is also the possibility of deep study of results, individual variables measuring and evaluating of the structure behaviour. Such thorough evaluation options cannot be fully applied in practice due to the disproportionately high cost of testing equipment. In the simulations, the following additional variables can be evaluated beyond the requirements of [7]:

- Energy balance of the calculation.
  Energy balance parameter to retrospective calculation check. Typical graph has characteristic course with gradually decreasing *Kinetic energy* while *Internal energy* rising up , see Fig. 35. Total energy does not include the work of the external forces as usual in Pam – Crash post processor (Visual Environment) [24].
- *Von Mises stress* and *Strain* distribution along the road barrier structure and main beams (guardrails).
- Deformation of each individual parts of the barrier.
- Plastic deformation, considering the strain method (tensile/compression).
- Contact force between the vehicle and barrier.
  The maximum peak of the force between the vehicle and the barrier can be determined from the contact force graph, see Fig.37. These values can be compared with theoretical design impact forces in [25] or [3].
- Acceleration and speed of the vehicle.
  Acceleration in vehicle is usually measured in COG or nearby. Signal is filtered by CFC60. Speed signal is gained by integration of the acceleration signal. Same approach is used in FEA output.

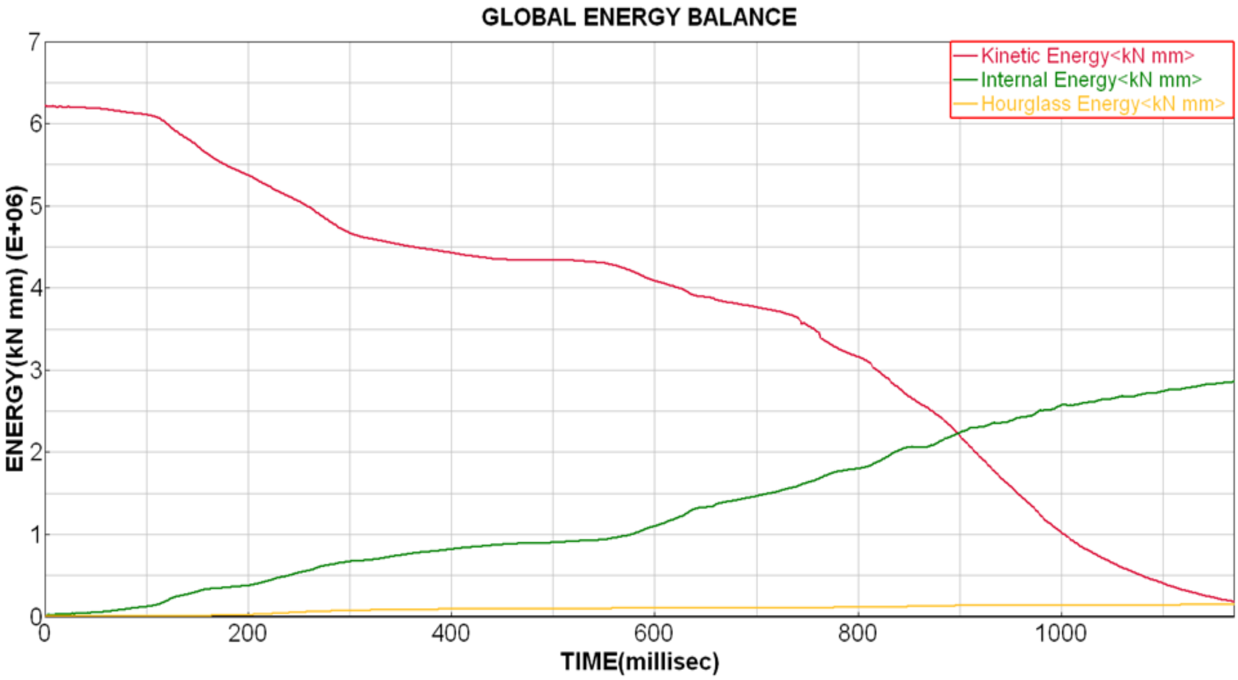


Fig. 35: Energy balance (Internal-Kinetic-Total) of the road barrier crash simulation

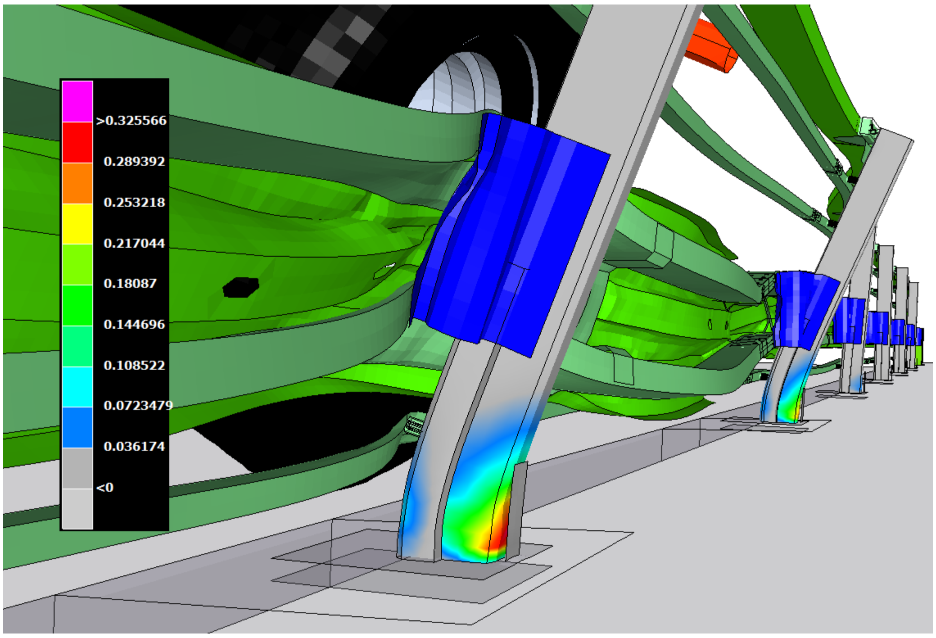


Fig. 36: Analysis of the RRS plastic strain under the impact conditions

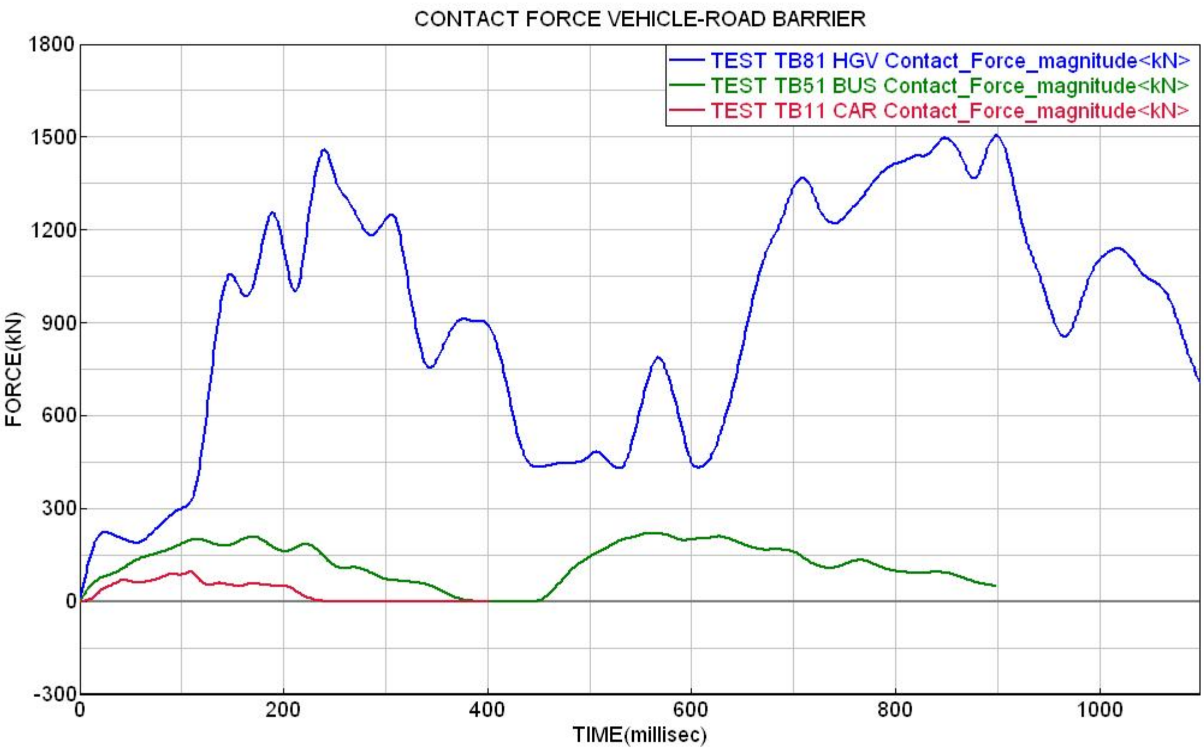


Fig. 37: Vehicle – road barrier contact force time history for TB11, TB51 and TB81 tests

10 Verification of crash test case studies

The chapter is introduced by the author's declaration referring to the numerical simulations:

Author declares that all models, simulations, and input conditions used in case studies were not unrealistically ex-post modified to achieve better correlation due to the knowledge of the real crash test results in advance.

When building FEM models, the simple and robust elements were deliberately chosen. These simulations do not include some specific tools with limited applicability (e.g. foam type of 3D solid elements for soil, tearing screws, sensitive failure mode for shell elements, nonlinear springs etc.) which are very sensitive to setup and may vary a lot. In such a case, it would be firstly necessary to debug, set up and validate separately.

Moreover, in the most practical cases, proper input of data is missing. This work is aimed to demonstrate the capability of numerical simulations to predict the behaviour and test results also with limited knowledge of input data.

The boundary and initial conditions of the simulations were adapted in accordance with the physical tests in range of:

- Initial velocity corresponds with testing impact speed.
- Impact vehicle mass corresponds to test mass.
- COG position of the vehicle or load (if known) was modified to the actual measured value.
- In some of the simulations the shape of the vehicle frontal parts was modified to be similar in shape to the actual impact vehicle.
- The height of the bridge parapet corresponds to a real test (if relevant).

Verification and conformity assessment of each simulation with the real test were conducted using the procedure from *Chapter 9 Crash model verification and evaluation.* Two different case studies verification are presented in thesis. Rest of the case studies verification is shown in Appendix 1.

10.1 Verification of case study no.1

Case study 1 represents the virtual picture of physical test TB 51. Test has been done with bus and road barrier made of steel installed (rammed) into the ground. Road barrier test sample is typical product used in the central Europe incl. Czech Republic.

Road barrier physical crash test

Bus hits the road barrier with the actual impact speed 71,45 km/h and actual angle 20,8 deg. Initial conditions are within the tolerance defined in EN1317. Actual impact speed and actual angle combination is also within the tolerance envelope defined in EN 1317.

During and after the impact no more than one wheel of the vehicle passes over the rearmost part of the deformed system. Vehicle does not roll over during the test and no more than 5% of the cargo has been separated in the vehicle till the stop. Information package related to the road barrier and crash test were completed by Technical Report from the physical test.

Crash test numerical simulation

With regards to the real tests the bus hits the road barrier 0,3m left from the post no.21. The initial conditions such an impact velocity; vehicle test mass and impact angle fully correspond with the real crash test values. Therefore, the impact energy 316,3 kJ is also the same.

Simulation models consist of these main parts:

- Impact vehicle:
    - Fully deformed vehicle with the kinematic suspension and rotating wheels, frontal area is smooth and flat – match with the real test vehicle.
    - Defined pressure inside the tyres –pressure vs. time function.

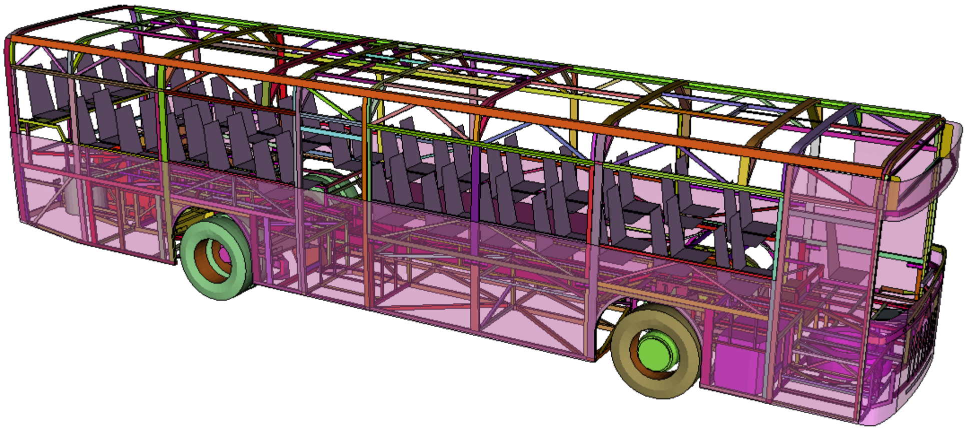


Fig. 38: FE model of the bus used in case study no.1

- Road:
    - Area for vehicle behaviour evaluation (9x105m).
    - Rigid body definition.
    - Nominal element length 1000mm.
- Road barrier FE model:
    - Total length of 105 m, incl. the leading and trailing parts.
    - Total of 90 posts totally fixed 270 mm under the road level. Depth of the fixation is based on the authors experience from the similar projects.

Fig. 39: Road barrier FE model

Entire model of the crash test consists of almost 935 000 elements. Nominal mesh size is defined with respect to the behaviour and expected deformation:

- Road barrier guard rail and posts – element length 12mm.
- Vehicle impact area: - element length 12 mm.
- Vehicle non-impact area - element length 50 mm.
- Road - element length 1000mm.

Overall view of the numerical model is shown in the Fig. 40.

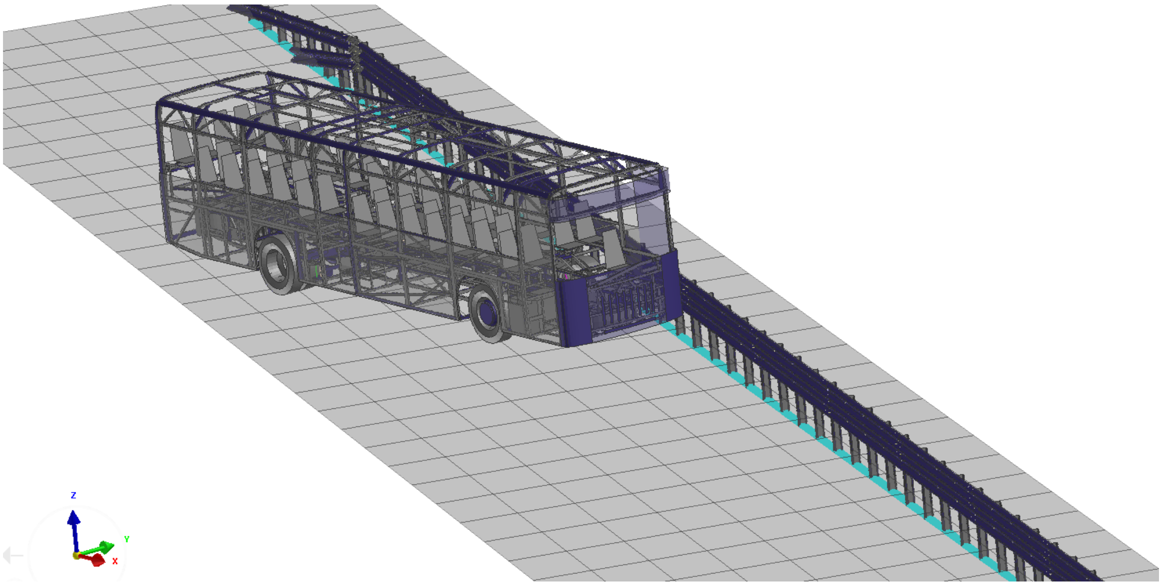


Fig. 40:Overall view of the numerical model from simulation no.1 – test TB51

Case study results

Vehicle impact to the road barrier is shown in the Fig. 41 and Fig. 42. Maximal residual deformation of the barrier compared to the real test is shown in Fig. 43. Top view of the impact divided into the image sequence compared to the real test is shown in Fig. 44 and Fig. 45.

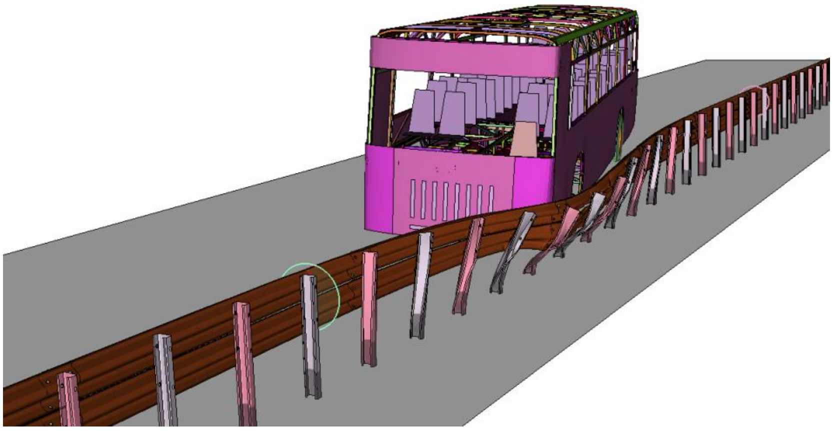


Fig. 41:Simulation no. 1 – Initial contact with road barrier

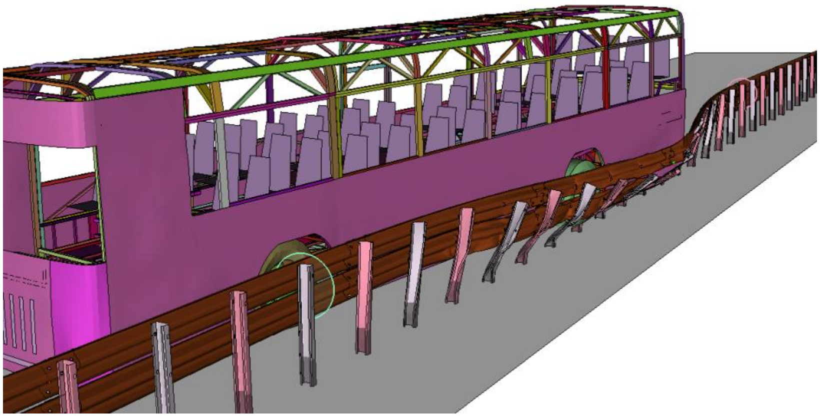


Fig. 42:Simulation no. 1 – Secondary contact with road barrier

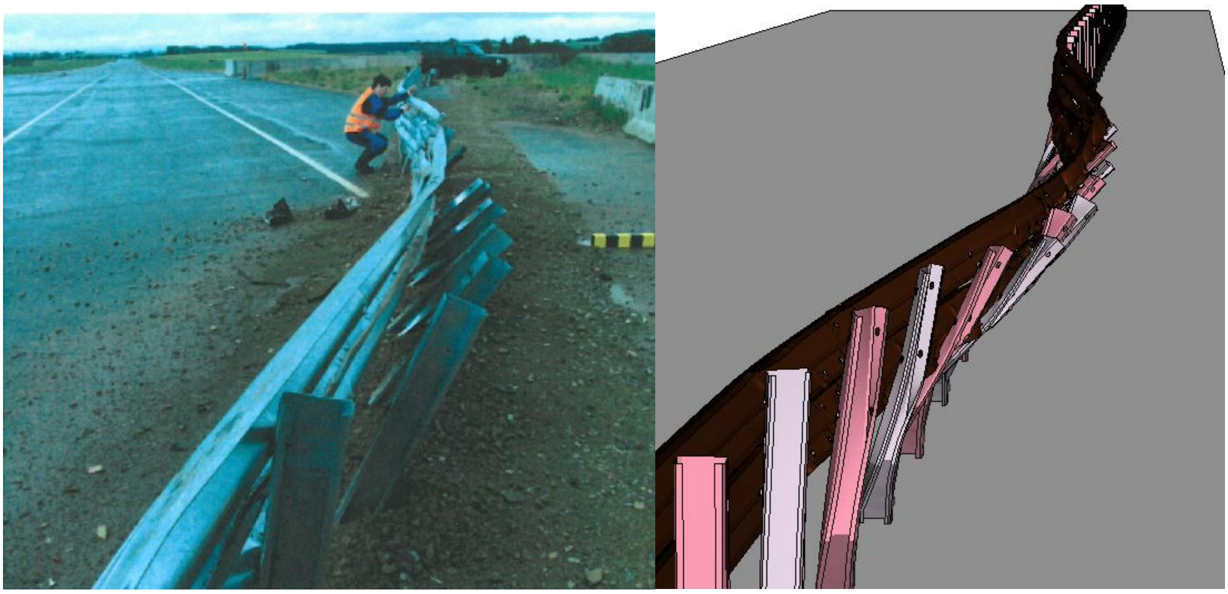
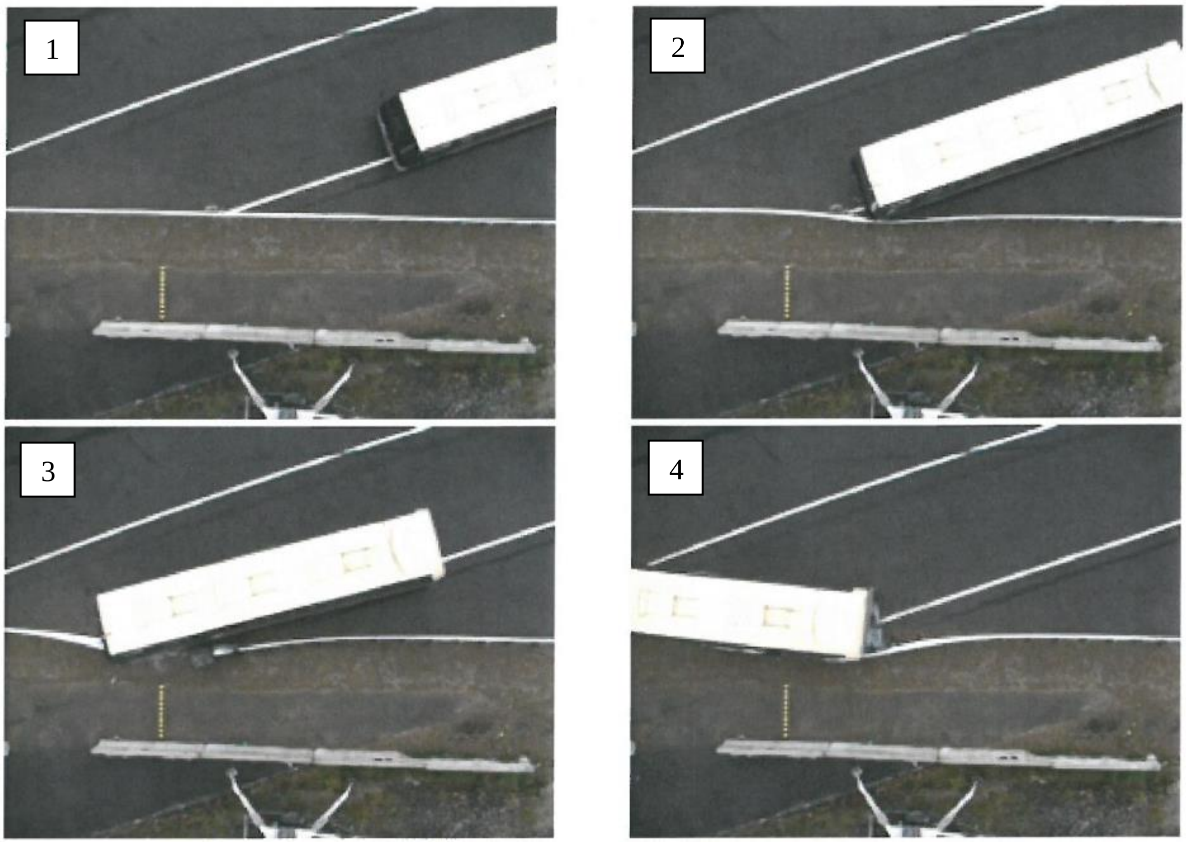


Fig. 43:Simulation no.1 – Road barrier permanent deflection –comparison real test – simulation



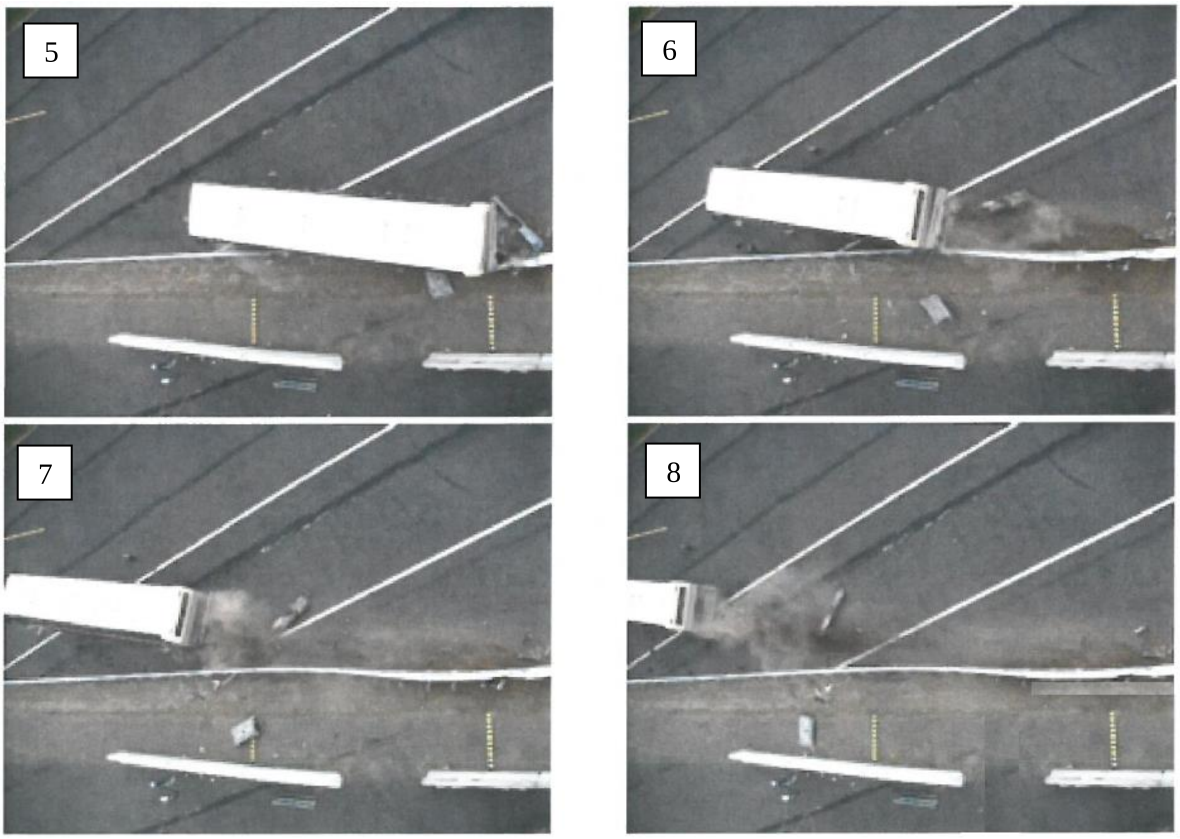


Fig. 44:Real crash test: Top view of the results

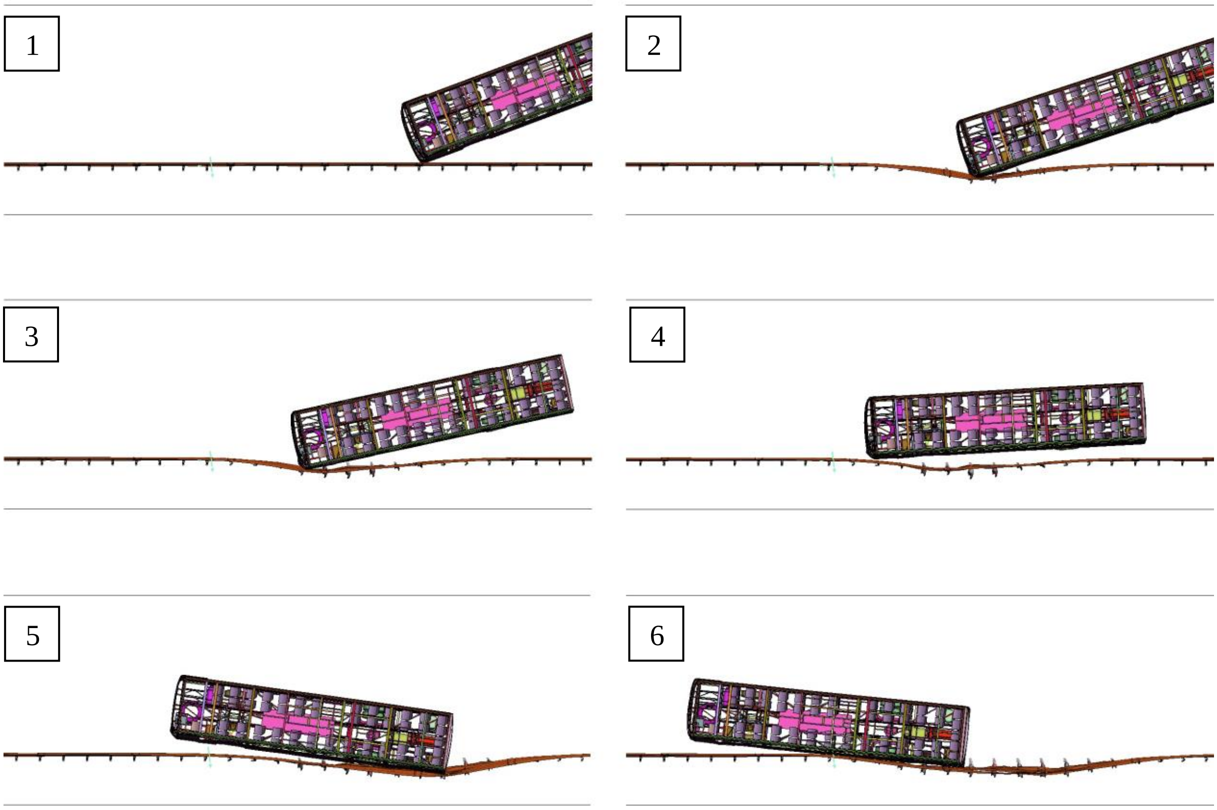


Fig. 45:Simulation no.1: Top view of the results

The evidence of the simulation validity is displayed on the output graphs in Fig. 46 -Fig. 48. Energy balance of entire simulation is shown in Fig. 46. It is obvious that calculation progress has no failure or unclear phenomena. Yellow curve represents the non- physical energy component (hourglass energy) and do not exceeds the recommended threshold of 4% of total energy. Smooth energy transformation among kinetic energy (red curve) and internal energy of the system (green curve) as expected.

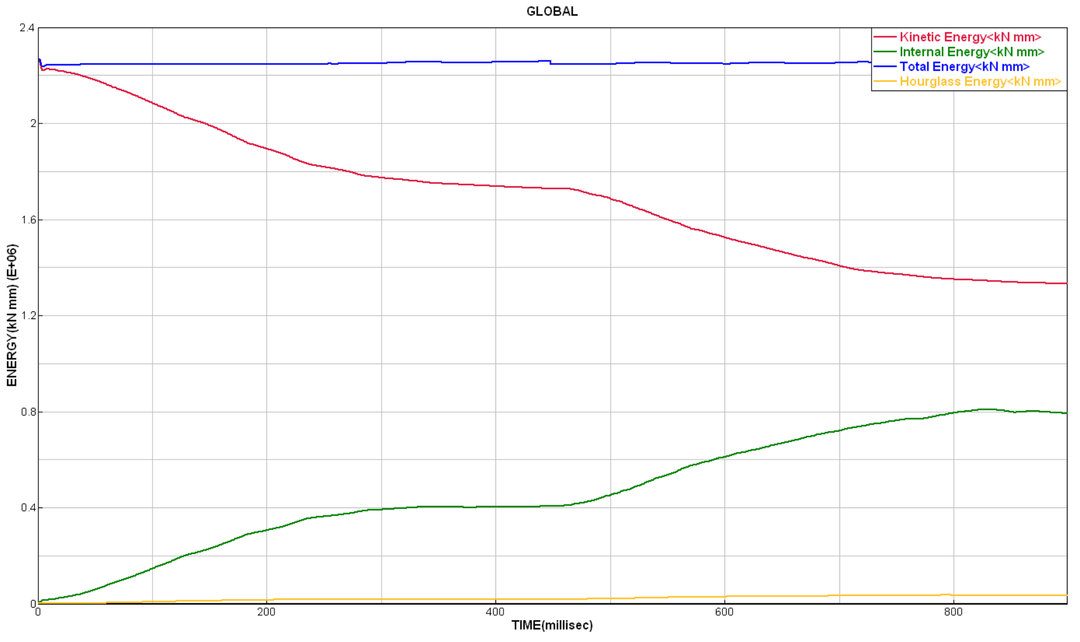


Fig. 46:Simulation case study no.1: Energy balance of the simulation

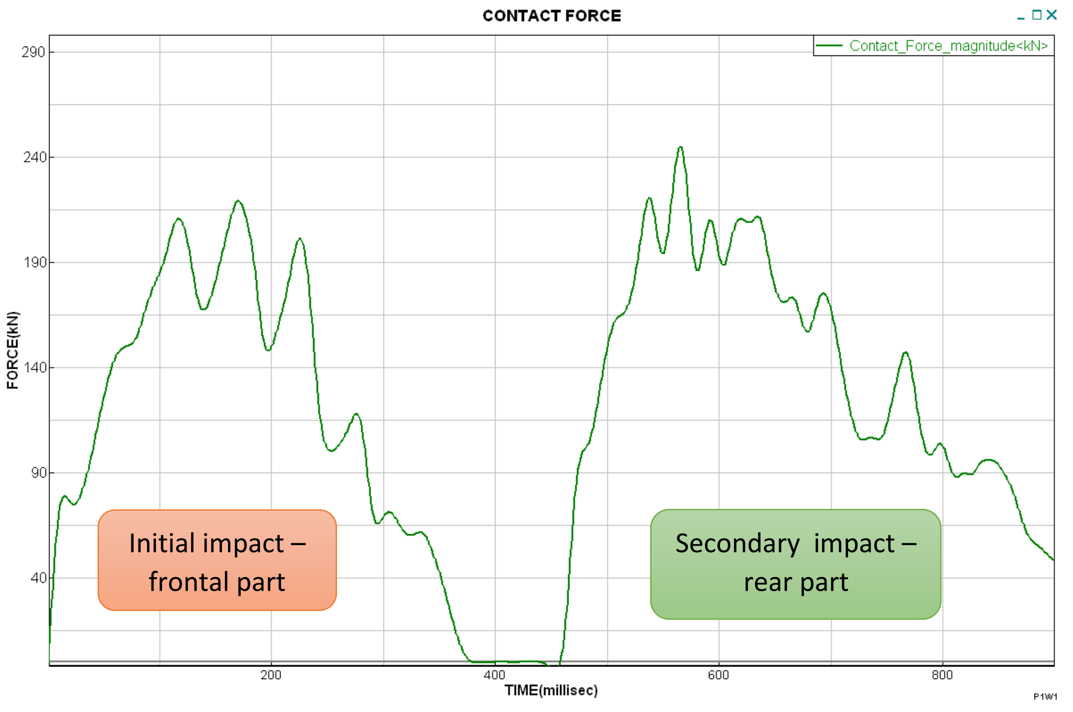


Fig. 47:Simulation Case study no.1: Vehicle – Road barrier contact force

Impact velocity time history is shown in Fig. 48. Initial impact velocity, their course during the impact and final velocity after the crash provide good match with the same in real test. Real crash velocity graph has been measured from paper technical report. Therefore, small difference in velocity course might not have been fully reflected.

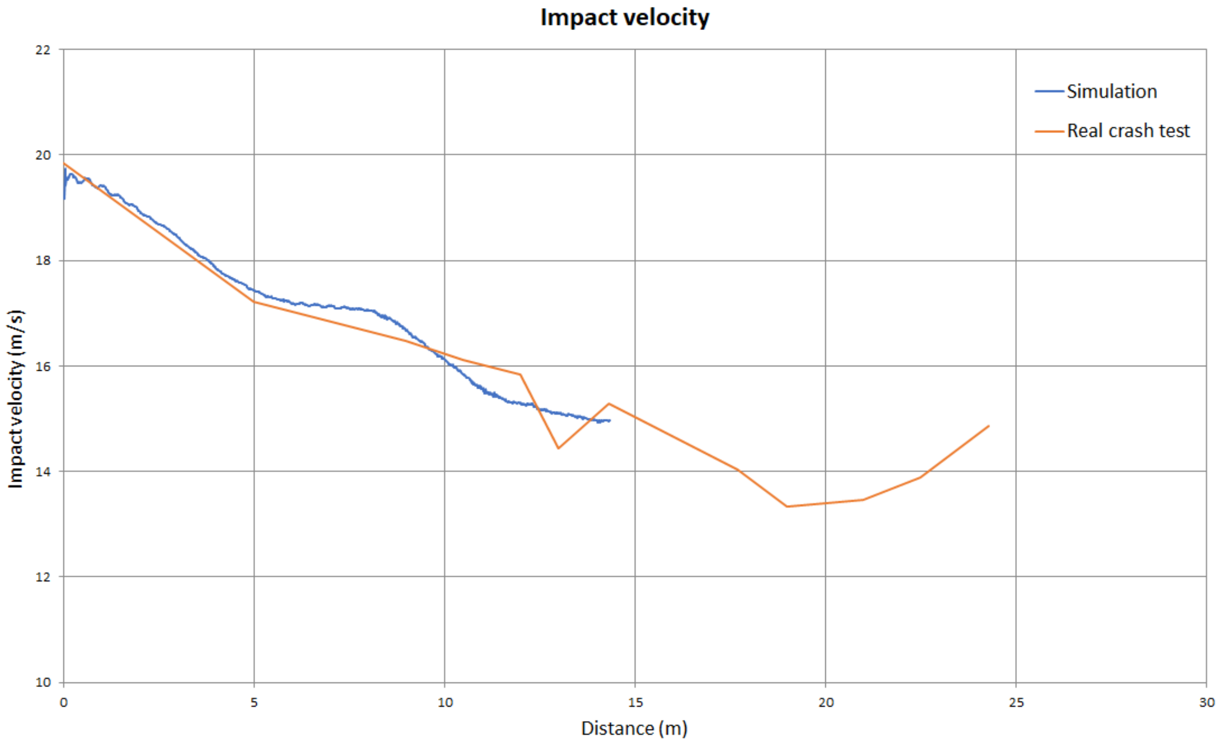


Fig. 48:Real test vs. Simulation: Vehicle velocity time history

Model verification – real crash test comparison

Main parameters of the numerical simulation incl. the simulation results have been compared with physical test results. Initial case study contains with detailed list of all test parameters, see Tab. 9.

Obviously, the virtual model cannot fully match in all parameters to the real test in first instance. The main difference we can observe in impact vehicle dimensions i.e. rear wheel track and some of the material mechanical properties. Their potential impact to the test results will be discussed further in the case study conclusion.

Tab. 9:Case study 1: Main parameters comparison: Physical test / Simulation

	Parameter	Physical Test	SIMULATION No.1	Difference
Initial conditions: Impact vehicle				
	Test Type acc. To EN 1317	**TB 51**	**TB51**	
	Vehicle type and model	KRAFTOMNIBUS N216, 1989	Bus model standard	
	Vehicle kerb mass [kg]	11700	N/A	N/A
	Total test mass [kg]	12735	12735	0
	Dimension – length [mm]	12000	11880	-1%
	Dimension – width [mm]	2500	2500	0
	Dimension – height [mm]	N/A	3275	N/A
	Wheelbase [mm]	6100	5950	-2,4%
	Wheel track – front [mm]	2100	2050	-2,4%
	Wheel track – rear [mm]	1800	2000	+11%
	Nb. of axles	1S+1	1S+1	--
	Tyre Radius [mm]	525	518	-1,3%
Impact conditions:				
	Actual impact speed [km/h]	71,45	71,45	0
	Actual impact speed [m/s]	19,85	19,85	0
	Actual impact angle [deg]	20,8	20,8005	0
	Impact Energy [J]	316293	316293	0
	Actual impact point location	0,3m left from post 31	0,3m left from post 31	0
	Test track condition	Wet	Frict = 0,4	--
Road barrier properties:				
	Material -overall	Steel	Steel	--
	Ground anchor	Ground	Posts fix in 0mm	--
	Ground anchor depth [mm]	900	140	--
	System width [mm]	232	232	0
	Post spacing [mm]	1000	1000	0
	Post cross section	C150x75x25 tl.3,5	C150x75x25 tl.3,5	0
	Post material (indication)	S420MC	S420MC	--
	Post Yield strength Re [Mpa]	420	420	0
	Post Ultimate strength Rm [Mpa]	480	550	+15%
	Post material Ductility A [%]	16	16	0
	Guardrail thickness [mm]	2,5	2,5	0
	Guardrail material (indication)	S420MC	S420MC	--
	Guardrail Yield strength Re [Mpa]	420	420	0
	Guardrail Ultimate str. Rm [MPa]	480	550	+15%
	Guardrail material - ductility A [%]	16	19	+19%
	Top Guardrail height - centre [mm]	830	830	0
	Low Guardrail height - centre [mm]	510	510	0

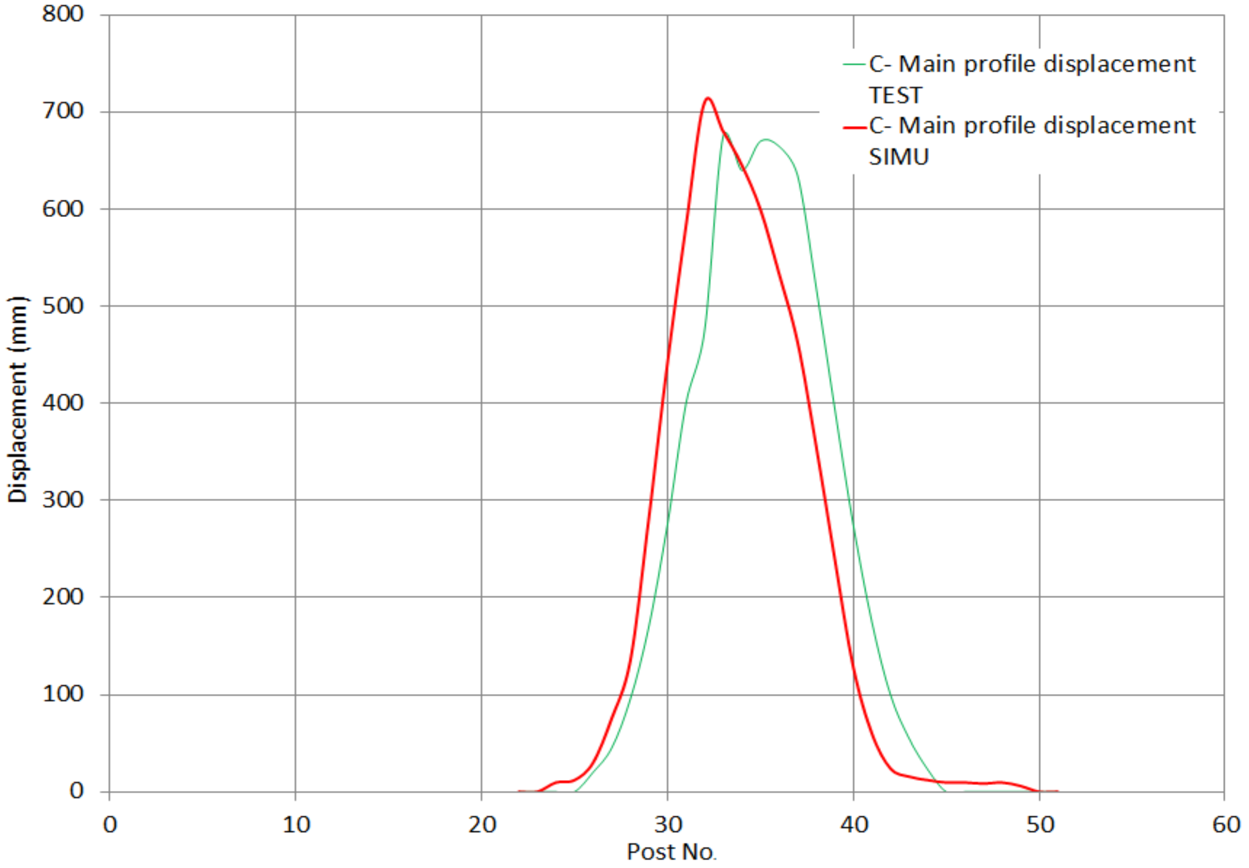


Fig. 49:Comparison of the post deformation (Test –Simulation)

10.2 Result evaluation – Case study no.1

The numerical simulation outputs of impact test No. 1 were compared with physical test, with regards to the test criteria for heavy vehicles:

- Acceptance criteria:
  - Point 1: Road barrier contained the test vehicle Y/N.
  - Point 2: Major parts (longitudinal elements) fractured or detached Y/N.
  - Point 3: Detached parts over the mass 2kg Y/N.
  - Point 4: Pieces of restraint system in cabin Y/N.
  - Point 5: Vehicle rolls over within the test Y/N.
  - Point 6: During the test no more than one-wheel passes over the rearmost part of the deformed system Y/N.
- Maximal dynamic deflection *D* in test.
- Maximal residual deformation after the test.
- Vehicle – road barrier contact length.
- Vehicle cockpit deformation index and overall vehicle deformation.

The results of comparison is summarized in Tab. 10, where all parameters are shown.

Tab. 10:Case study 1: Simulation – physical test results comparison

Parameter		Physical test	Simulation	Difference
Acceptance criteria	Pnt.1: Vehicle contained	Y	Y	OK
	Pnt. 2: Major parts detached	N	N	OK
	Pnt. 3: Detached parts over 2kg	N	N	OK
	Pnt. 4: Pieces in cabin	N	N	OK
	Pnt. 5: Vehicle rolls over	N	N	OK
	Pnt. 6: One-wheel passes over the rearmost part of the system	Y	Y	OK
Maximal dynamic deflection		0,86 m	0,83 m	-3.5%
Maximal residual deformation		0,68 m	0,71 m	+2.9%
Vehicle intrusion		1,1 m		
Contact length		10,8 m	9,53 m	-11.8%
Vehicle cockpit deformation index		000000	0000000	OK

Results discussion – case study no.1

Test acceptance criteria and other parameters of the simulation match with the physical test correctly, with acceptable difference. Vehicle (Acceptance criteria Point 5,6, VCDI index) and barrier (Acceptance criteria Point 1-4) behaviour within the test is correctly modelled. Acceptable difference for the aim of this work is up to 10% from the physical test values, for main parameters e.g. dynamic deflection D or residual deformation.

The maximal error is referring to the length of the contact between the impacting vehicle and the road barrier. This error in real values slightly exceeds the limits for acceptability above. However, in percentage it is close to 12%. There are few explanations of this difference.

- Friction coefficient between the vehicle body and road barrier as well as tyres and ground are lower in simulation.
- Frontal stiffness of the vehicle is different compared to the physical test
- Steering of the vehicle has different properties (system resistance, mech. characteristics etc.)

Maximal dynamic deflection of the road barrier *D* in simulation is also lower. Contrary, the residual post deformation is slightly higher. The explanation of this we should find in material properties and bolt connection modelling. Material of the main barrier parts has likely different mechanical properties in physical test i.e. the definition of Young modulus and plastic zone in stress-strain diagram. Also, the modelling of the connection bolts is simplified. Therefore, effect of the guard rail pull-out as is shown in Fig. 50 has impact on physical test results.

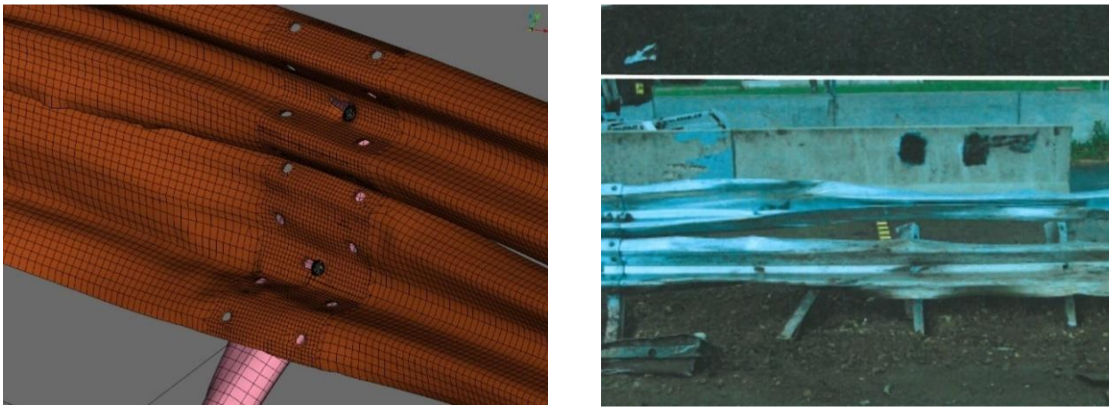


Fig. 50:Comparison of the post deformation in impact point (Simulation –Test)

Next step simulation could implement some corrective measures in order to get more realistic results. Since reverse engineering approach is not aim of this work, next simulation has not been done. Results from the simulation case study no.1 represent the physical test correctly with acceptable difference.

10.3 Verification of case study no.2

Next case study represents the typical test of type TB 11. Test TB11 is an integral part of approval testing procedure aimed to check the system convenience in case of the lightweight car impact. The physical test has been conducted with lightweight passenger car (Peugeot 106, 880kg) and road barrier made of steel installed (rammed) into the ground. This test is fundamentally different in the matter of evaluation, with a focus on the occupants load during the impact and vehicle exit trajectory.

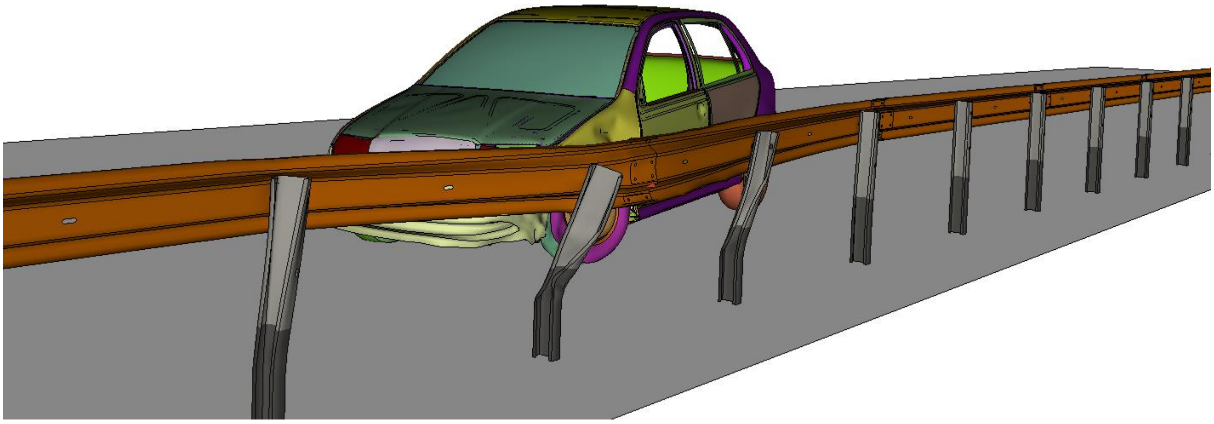


Fig. 51:Simulation of case study no 2 – Initial contact with road barrier

Road barrier crash test

Vehicle hits the road barrier with the actual impact speed 101,57 km/h and actual angle 20,3 deg. Initial conditions comply with the tolerance defined in EN1317. Combination of the impact speed and angle is inside the tolerance envelope box defined in EN 1317. Physical crash test information has been completed by Technical Report.

The results were compared with regards to the test criteria for small lightweight vehicles. Main criteria are the same as in previous test. Evaluation of the results is completed with crew load criteria Impact severity index ASI and theoretical head impact velocity THIV. For more details referring to simulation model, test comparison and evaluation see Appendix 1.

Fig. 52:Case study no 2. – Road barrier permanent deflection –comparison real test – simulation

Complete validation of entire model is shown in Appendix 1. Main results correlation (agreement with the physical crash test) and errors are summarized in Tab. 11.

Tab. 11:Simulation – physical test results comparison

Parameter		Physical test	Simulation	Difference
Acceptance criteria	Pnt.1: Vehicle contained	Y	Y	OK
	Pnt. 2: Major parts detached	N	N	OK
	Pnt. 3: Detached parts over 2kg	N	N	OK
	Pnt. 4: Pieces in cabin	N	N	OK
	Pnt. 5: Vehicle rolls over	N	N	OK
	Pnt. 6: One-wheel passes over the rearmost part of the system	Y	Y	OK
Maximal dynamic deflection		0,43 m	0,45 m	+4.7%
Maximal residual deformation		0,26 m	0,27 m	+3.8%
Contact length		6,59 m	4,8 m	-27.2%
Vehicle cockpit deformation index		000000	0000000	OK
Impact severity index ASI		0,67	1,3	+94,0%

10.4 Results evaluation -case study no.2

Results analysis were split into two groups, because of the test with small car.

- 1 - representation of the road barrier behaviour. There are all acceptance criteria (Point 1-6) and Dynamic deflection, Residual deformation, and Contact length parameters to verify.
- 2 - parameters referring to the impact vehicle itself and occupant load, e.g. ASI index, THIV and VCDI.

The maximal acceptance criteria error is referring to length of the contact. This error in real values exceeds the limits for acceptability above, in percentage is 27,2%. However, the difference in contact length in real numbers is 1,8m.

This effect could be partially caused by Vehicle- Barrier contact definition e.g. high friction coefficient and vehicle FE model itself as well. The possible cause will be discussed in next paragraph.

Test acceptance criteria referring to the impact vehicle does not provide as good conformity as expected. The maximal error is referring to the ASI index. This error in maximal value significantly exceeds the limits for acceptability above, in percentage is 47,7%. There are three main effects to explain the difference in ASI numbers.

- Vehicle frontal stiffness is different compared to the physical test.
- Steering of the vehicle has different properties (system resistance, mechanical characteristics etc.).
- Friction coefficient between the vehicle body and road barrier as well as tyres and ground in simulation is different.

Impacting vehicle model plays key role in small car tests i.e., TB11, TB21, TB22, TB31 and TB32. FE model of the passenger cars are usually simplified or modified from different vehicles. This finally leads to possible significant errors in evaluation parameters, for instance ASI, THIV and VCDI even if the rod barrier behaviour is correct.

Complete results comparison of all cases studies is summarized in Appendix 1: Case studies simulation results and verification.

10.5 Verification results discussion

Total of 8 road barrier crash scenarios were prepared and analysed within the thesis framework. Simulations were compared with their physical test twins. The analysis outputs show that modelling procedure, as is shown in this work provides sufficient and predictive results. Therefore, verification process finished successfully. At the same time a certain principal limitation has been identified and described. Suitable corrective measures are also proposed for next step application. These constraints are particularly:

- Acceleration severity index ASI evaluation based on the acceleration measurement could provide uncertain results, differs from physical tests. This feature has been observed in all simulations with the small passenger car tests- mainly the tests TB11.
- Simulation time is limited due to the cumulation of numerical error. More than 1000ms of the simulation time is not recommended. Therefore, evaluation of the vehicle trajectory after impact is limited.
- Soil mechanical properties are indirectly represented by depth of the post fixation (under the road level). The fixation depth affects the simulation result in the same manner, even if has no reference to soil conditions.
- Coincidence event effect e.g., tyre puncture or cargo separation within the test cannot be fully predicted by simulations.
- Concrete road barrier or concrete bridge parapet damage.

Most of the road barriers in case studies have certain safety margin in case of the heavy good vehicle impact. Contrary, some of them are close to their limits, what confirms the statement in foreword of this thesis.

Proposed modelling procedure, which was used in the case study simulations, provide an acceptable match with the physical tests in all defined criteria. Modelling procedure is validated and can be used for further investigation within the thesis as well.

11 Sensitivity analysis of the model uncertainties

Model uncertainties referring to physical test results have been studied on selected case study scenario. Numerical model was used from previous thesis part "Road barrier crash analysis". Case study represents the test TB51 with 13 t bus and 70kmph impact. The model uncertainty effects were applied as a variation of the FE model parameters in simulations. Maximal limit for testing accuracy from EN1317 has been considered in order to get reasonable extreme values. Values outside the limits mean that the test results cannot be accepted. These cases are not relevant for the study. The initial conditions play key role in case of the HGV impact due to the several reasons:

- Impact energy effect. If the impact energy is so high and road barrier structures could be close to their structural resistance limit. Therefore, relatively small change in the impact conditions could finally leads to very different test results.
- Vehicle types and design of the impact vehicle used for a test may vary a lot. Despite clear definition of vehicle parameters (mass, loads, COG position etc) in EN1317, the structural differences in design may affect the result significantly.

At least 20 simulations to analyse the model uncertainties were assessed. Analysis results could be abstract to most of the steel road barriers.

Initial conditions uncertainties

1/Initial conditions cannot acquire any values. For example, the impact velocity must be in range from 69 to 75kmph. When exceeds the limits, the physical test was failed. Other initial condition values (impact mass and angle) have also their limits – see Tab. 12 and Tab. 13.

- Vehicle mass deviation.

Tab. 12:Vehicle mass deviation

Test	Nominal mass	Upper limit	Lower limit
TB11 (light car impact)	900 kg	860 kg	940 kg
TB 51 (Bus impact)	13 000 kg	12 600 kg	13 400 kg
TB81 (LGV impact)	38 000 kg	36 900 kg	39 100 kg

- Vehicle impact velocity deviation
  Two tolerances should be considered. The maximal error of the velocity measurement is +/-1%. And deviation of the impact velocity must be in range 0, +7%. Impact velocity limits are shown in Tab. 13 and graph in Fig. 53:

Tab. 13:Limits for impact velocity in the model uncertainties analysis

Test	Nominal impact velocity	Upper limit	Lower limit
TB11 (light car impact)	100 kmph	108,08 kmph	99,0 kmph
TB 51 (Bus impact)	70 kmph	75,6 kmph	69,3 kmph
TB81 (LGV impact)	65 kmph	70,0 kmph	64,3 kmph

- Impact angle deviation
  Maximal allowed deviation of the impact angle is also defined in EN1317. Actual impact angle, measured in the test must be in range from -1% to +1,5% of the nominal impact angle. The combination of the impact angle and speed deviation must be within the limits shown in Fig. 53.

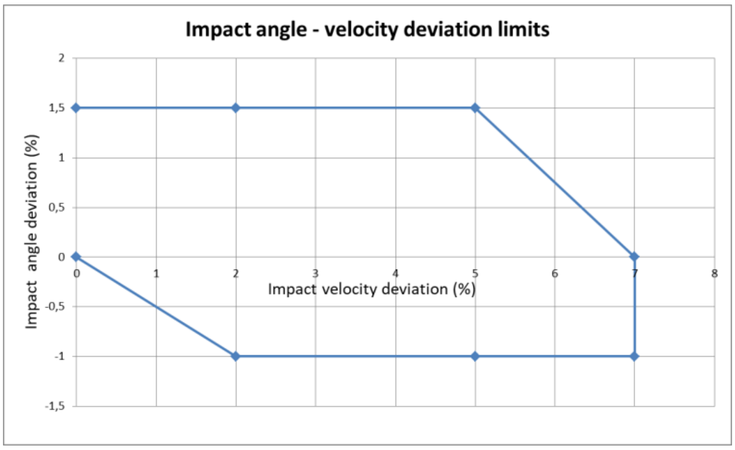


Fig. 53:Impact angle and velocity deviation limits

2/Uncertainty refers to natural test features, with impact to the results and has no relationship with initial conditions, e.g.:

- Tyre puncture and discharge in the test – can acquire Yes/No state only
  Computational simulation is not capable to predict tyre puncture and discharge. Therefore, there are two almost identical simulations with two different setups of the pressure inside the tyres – see Fig. 54. Therefore, we can identify its possible impact on the test results.

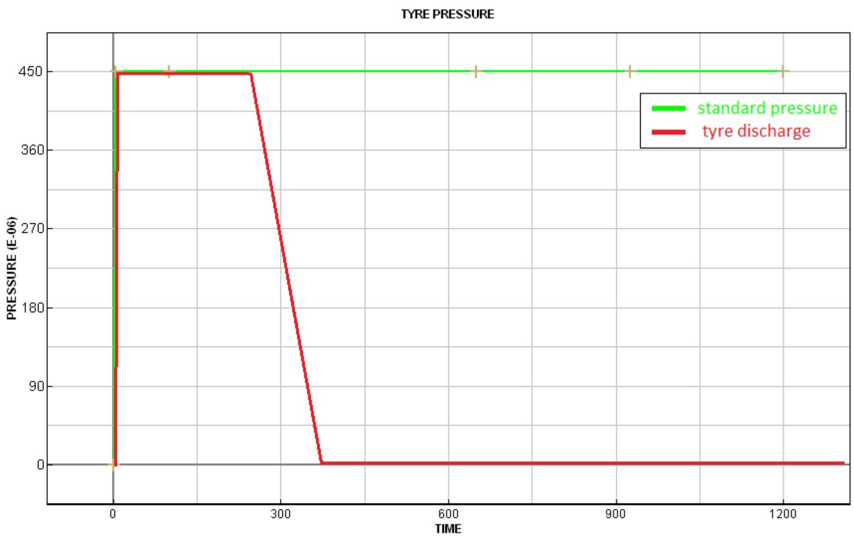


Fig. 54:Tyre pressure function in simulation, discharge effect

Tyre defect and discharge at a given time can fundamentally affect the behaviour of the vehicle within the impact, the trajectory in exit area. During an impact, it may affect the interaction between the vehicle and road barrier. The simulations show that rather towards to worse results, e.g. Dynamic deflection *D*. The trajectory on the exit area is mostly affected towards to better results. Front wheel usually breaks closer to the barrier and due to greater friction of flat tyre; the vehicle tends to turn towards the barrier. This feature is assessed in the exit area.

Note: Time when the tyre is discharged can also affect the simulation results. However complex analysis exceeds the thesis framework.

- Soil mechanical properties
  Simulations with different depth of the posts anchorage can be used to define the influence of the soil mechanical properties to the test result. Simulation with anchorage depth of 200 mm

represents relatively soft soil and 0mm (on the road level) represents the soil with hardest mechanical properties. Finally, this approach simplifies the reality a lot because the posts anchorage depth has no direct relationship to soil mechanical properties. Many simulations show that this representation of the soil is reasonable.

Therefore, two simulations with different anchorage depth (h=200mm and h=lim →0mm) were done to define the soil mechanical properties as a model uncertainty – see Fig. 55.

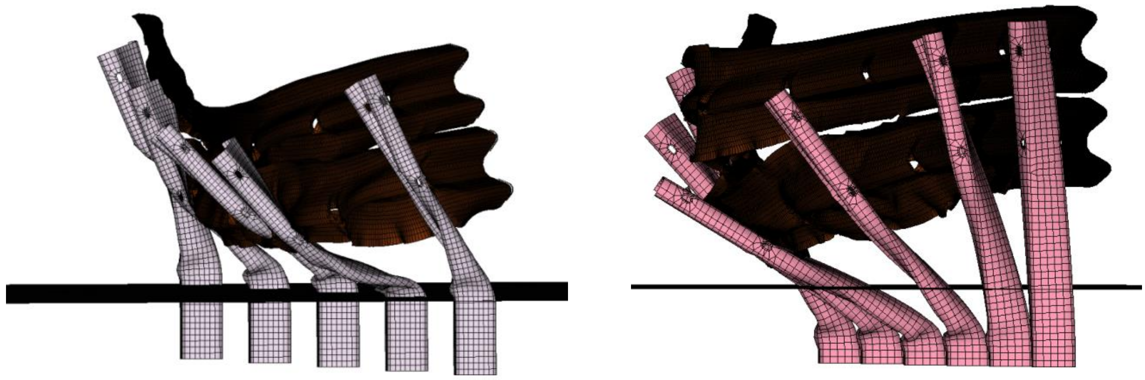


Fig. 55:Post anchorage depth affects the simulation results (left 0mm, right -200mm)

Note: Unfortunately, the simplification of the soil properties, how is shown in this article cannot reflect the "posts pull-out effect". This feature is one principal approach constraint. Contrary, pull out effect of the posts is not common phenomena. Author observed in test results once time only (and finally this test has been cancelled due to this reason).

11.1 Evaluation of model uncertainties results

Dynamic deflection results for Case study as a function of initial conditions deviation are displayed in Tab. 14 - Tab. 17. Particularly, the tables combine the contribution of *Impact Angle x Vehicle Mass* / *Impact Angle x Impact Velocity* / *Impact Velocity x Vehicle Mass* on simulation result. The values in brackets represent the percentage value relative to the real test results, which is 0,86 m.

Tab. 14:Model uncertainties analysis– Dynamic deflection as the function of *Mass* and *Impact velocity*

		Velocity [kmph]			
		Min	Nominal	Test	Max
	Mass [kg]	69.33	70	71.45	75.66
Min	12600	0.798 (92,8%)	0.836 (97,2%)	0,842 (97,9%)	0.836 (97,2%)
Test	12735	0,815 (94,8%)	0,822 (95,6%)	0.834 (97,0%)	0.831 (96,6%)
Nominal	13000	0.838 (97,4%)	0.844 (98,1%)	0,855 (99,4%)	0.855 (99,4%)
Max	13400	0.861 (100,1%)	0.873 (101,5%)	0,876 (101,9%)	0.884 (102,8%)

Tab. 15: Model uncertainties analysis – Dynamic deflection as the function of *Angle* and *Impact vel.*

		Velocity [kmph]			
		Min	Nominal	Test	Max
	Angle [deg]	69.33	70	71.45	75.66
Min	19.8	0.856 (99,5%)	0.831 (96,6%)	0,838 (97,4%)	0.904 (105,1%)
Nominal	20	0.838 (97,4%)	0.844 (98,1%)	0,840 (97,7%)	0.855 (99,4%)
Test	20.3	0,860 (100%)	0.875 (101,7%)	0,879 (102,2%)	0.905 (105,2%)
Max	20.8	0.878 (102,1%)	0,892 (103,7%)	0.882 (102,6%)	0.922 (107,2%)

Tab. 16: Model uncertainties analysis – Dynamic deflection as the function of *Mass* and *Impact angle*

		Angle [deg]			
		Min	Nominal	Test	Max
	Mass [kg]	19.8	20	20.3	20.8
Min	12600	0.835 (97,1%)	0.846 (98,4%)	0,835 (97,1%)	0.833 (96,9%)
Test	12735	0,840 (97,7%)	0,852 (99,1%)	0,831 (96,6%)	0.834 (97,0%)
Nominal	13000	0,850 (98,8%)	0.844 (98,1%)	0,832 (96,7%)	0,844 (98,1%)
Max	13400	0.871 (101,3%)	0.873 (101,5%)	0,881 (102,4%)	0.908 (105,6%)

Moreover, two additional simulations with extreme values of the initial conditions were assessed. Details are shown in Tab. 17.

Tab. 17: Model uncertainties analysis – Dyn. deflection as the function of extremal initial conditions

	Angle [deg]	Velocity [kmph]	Mass [kg]	Dynamic def. [m]
IC ALL MAX	20.8	75.66	13400	0.95 (110,5%)
IC ALL MIN	19.8	69.33	12600	0.815 (94,8%)

Dynamic deflection results, specified above are particularly shown in 2D or 3D surface graphs form, see Fig. 56 and Fig. 57. Rest of the case studies results are summarized in Appendix 1.

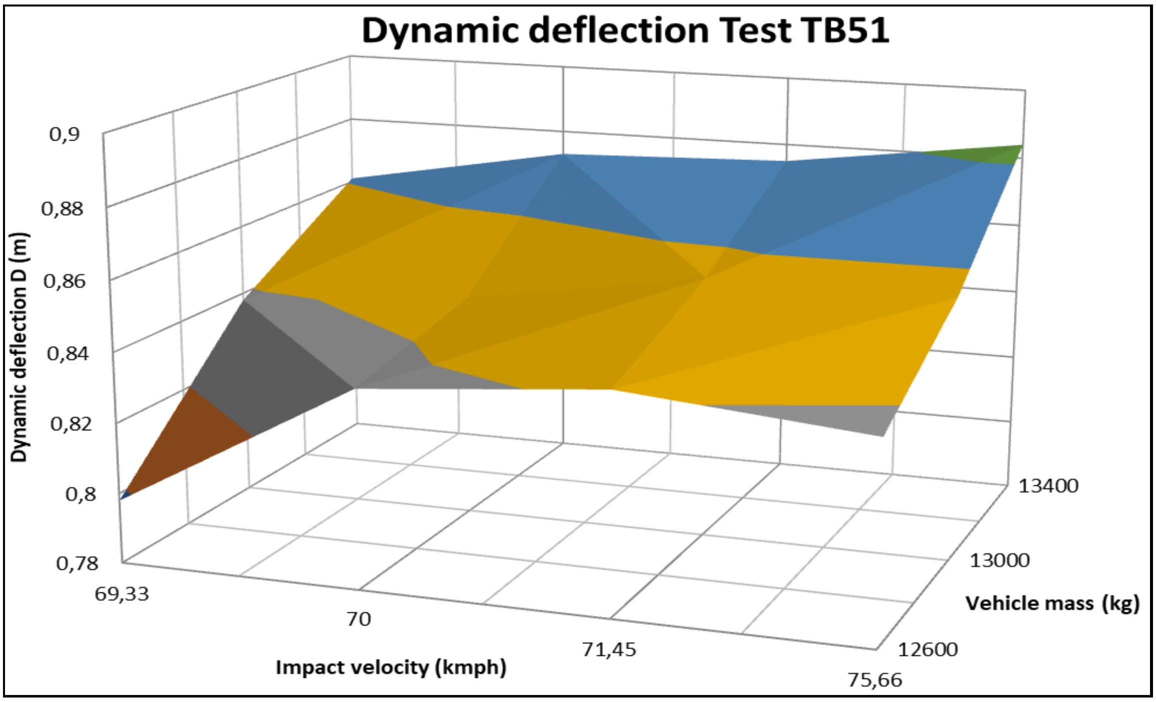


Fig. 56:Response surface for Dynamic deflection (Impact velocity – vehicle mass)

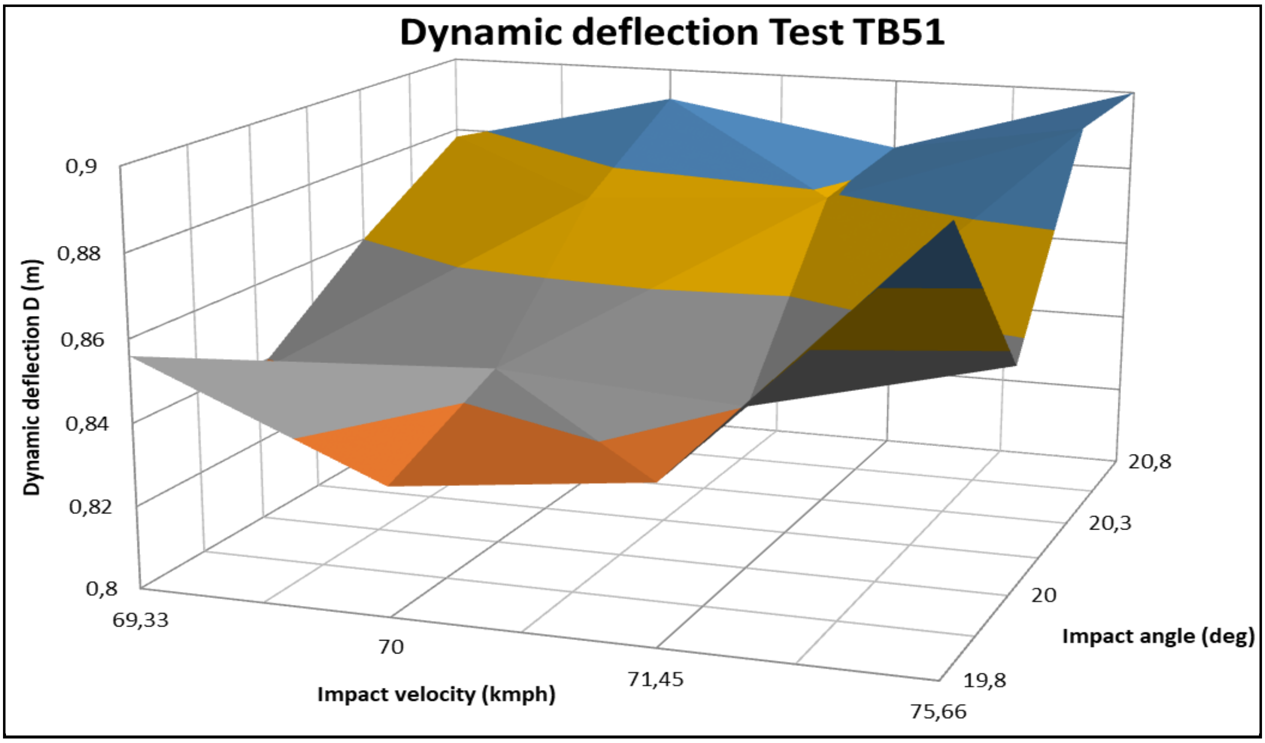


Fig. 57:Response surface for Dynamic deflection (Impact velocity – impact angle)

The following graphs shows dependency of two initial condition values, while the last value remains on nominal level. Fig. 58 shows effect of the vehicle mass on test result, for different impact velocity, while impact angle remains the same, at nominal value 20 deg.

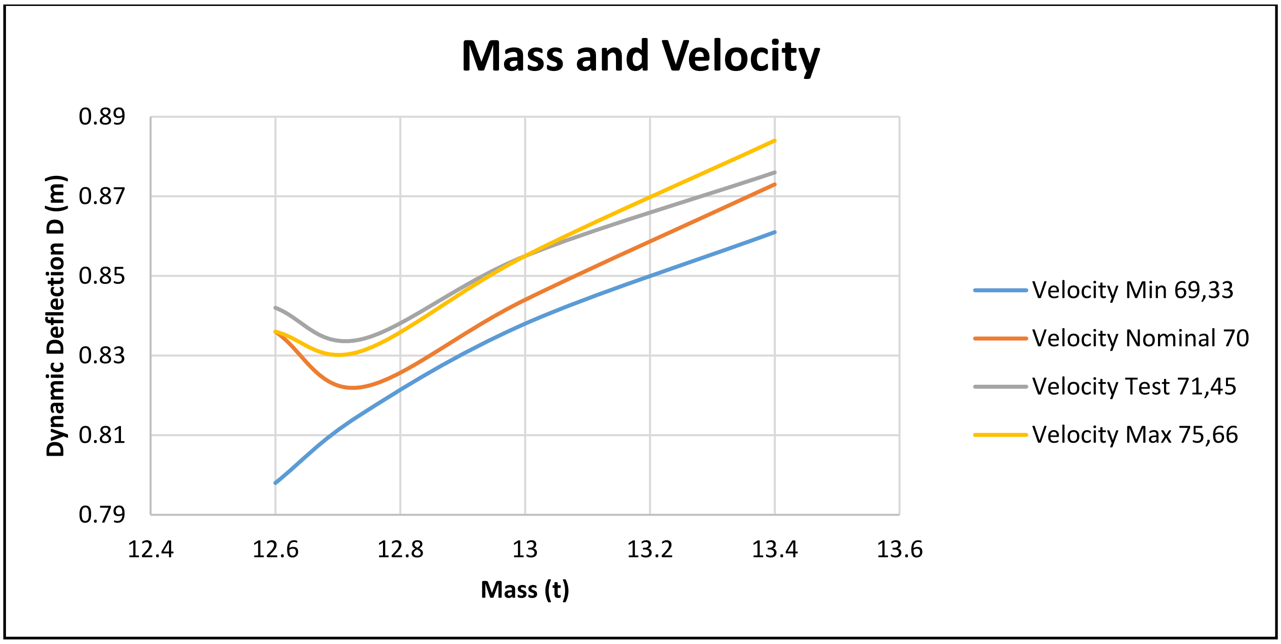


Fig. 58:Sensitivity analysis results – vehicle mass effect on result for different impact velocity

Fig. 59 shows effect of the impact angle on test result, for different impact velocity, while vehicle mass remains the same, at nominal value 13000 kg.

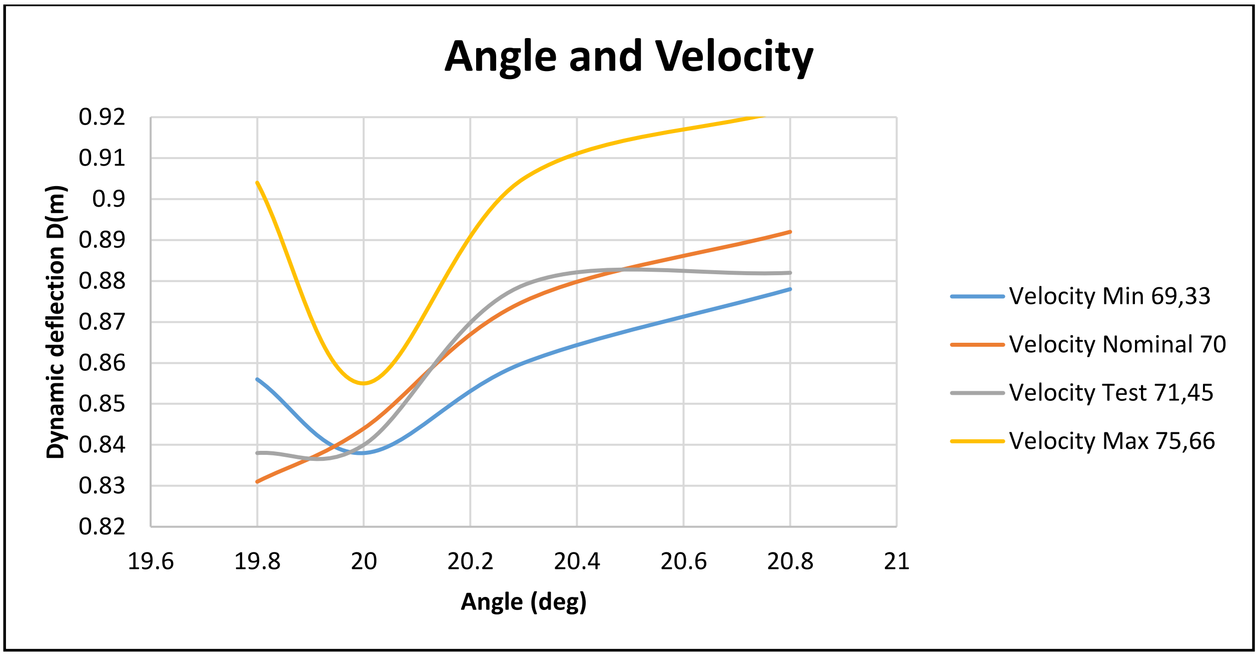


Fig. 59:Sensitivity analysis results – impact angle effect on result for different impact velocity

Last graph in Fig. 60 shows effect of the vehicle mass on test result, for different impact angle, while impact velocity remains the same, at nominal value 70 kmph.

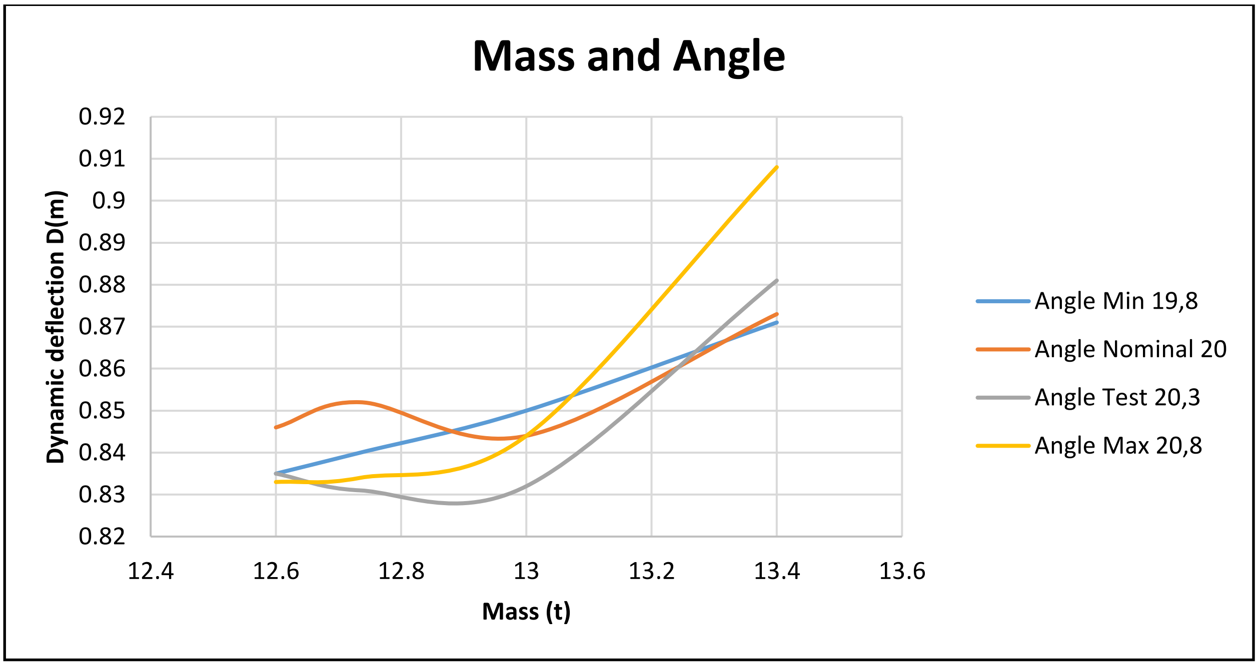


Fig. 60:Sensitivity analysis results – vehicle mass effect on result for different impact angle

From the graphs in Fig. 59 and Fig. 60, it is obvious that impact angle has no significant effect on the test results in our representative example. All initial conditions effect is possible to represent via impact energy parameter. Therefore, the sensitivity analysis results can be simplified to impact energy/deformation graph, as is shown in Fig. 61. Each of the points represents one simulation from the Tab. 14 - Tab. 17. Impact energy E_{imp} is given:

$$E_{imp} = 1/2\ m.(v.\ sin\varphi)^2$$

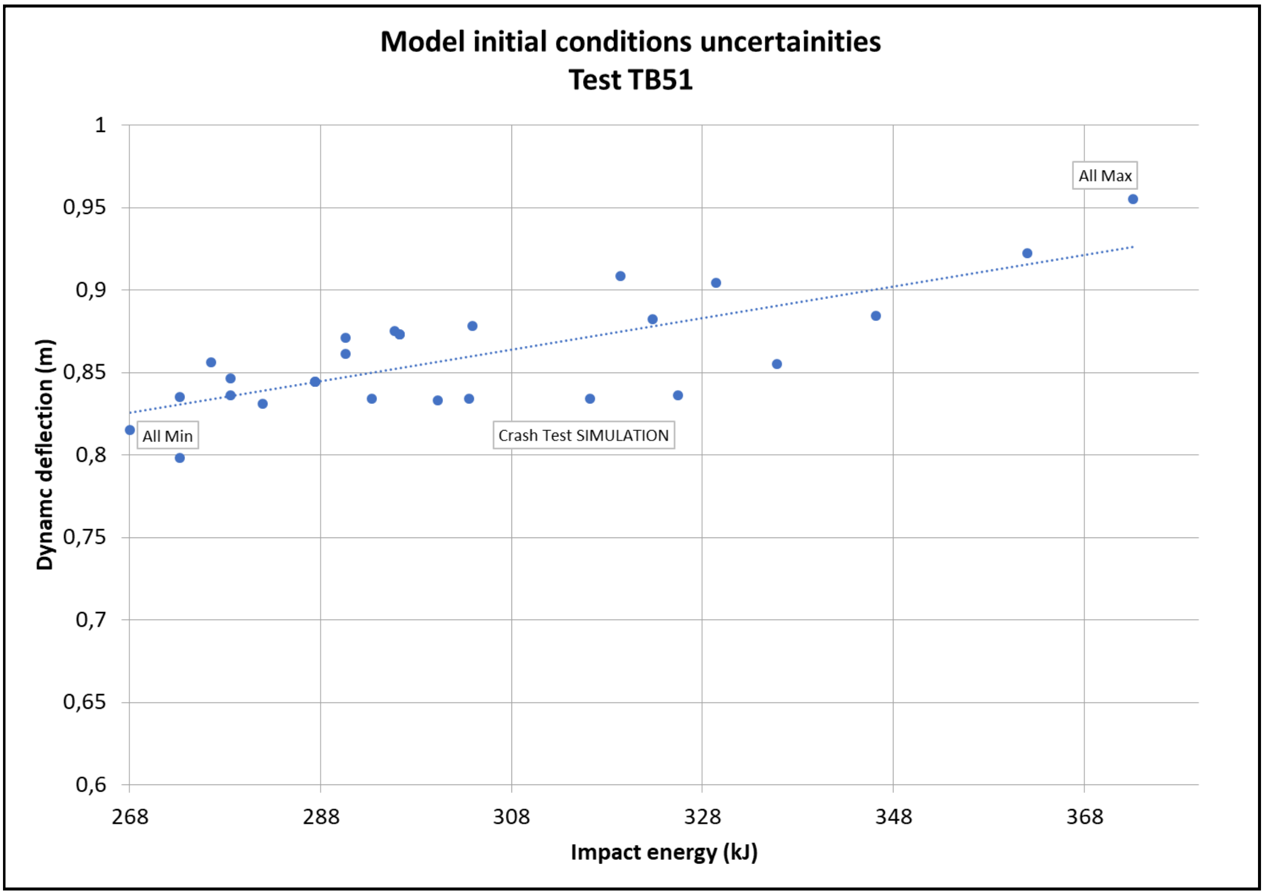


Fig. 61:Sensitivity analysis results: Impact energy – Dynamic deflection

Result Discussion

More than 25 simulations with different initial conditions were done to analyse the impact of the model uncertainties to the test results. The maximum total difference in the result of *dynamic deflection D* between two extreme tests is 0.14 m, which is 16.3% of the result of the crash test simulation.

Evaluation of the tyre puncture and discharge effect in the test

The effect of the tyre discharge was studied in two of the model uncertainties simulation case studies. Despite the assumptions, the impact test did not change due to the flat tyre.

There is a possibility to evaluate the model uncertainties impact on other test result parameters e.g.:

- Vehicle intrusion (VI)
- Vehicle – barrier contact length
- Impact severity index for test TB11 (light car impact)
- Vehicle-barrier contact force (peak@ time)

These parameters have not been evaluated, although simulation results files contain of all information.

12 Application of NLDFEA in probabilistic assessment methods

Use of nonlinear dynamic analyses as a tool for the probabilistic assessment of a road barrier structures is a rather unique approach so far. Probabilistic assessment approach (see section 3) can be applied to road barriers structures as well. Probabilistic approach gives to designer a very concrete overview of the reliability of the structure, in the following situations:

1/ Road barrier loading due to unintentional vehicle impact.

2/ Mandatory impact crash test or conformity assessment of the modified barrier structure.

Diagram of the usage of probabilistic methods for the design or assessment of a road barrier is given in Fig. 62.

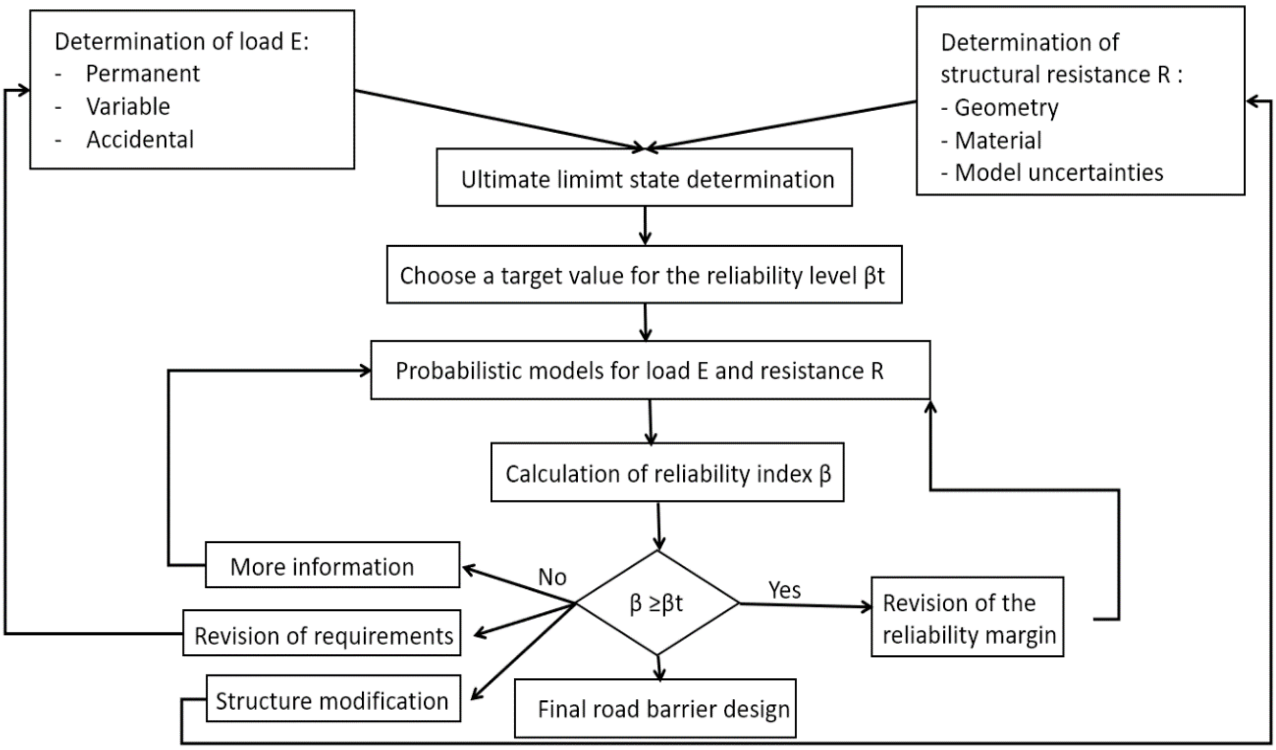


Fig. 62:Road barrier reliability assessment diagram

12.1 Probabilistic model of accidental impact loading

The aim is to verify the reliability of the structure under accidental loading, i.e. impact loading that may occur in real life of the structure.

The impact load model is based on the general vehicle lane leaving and collision into the obstacle (see section 3.7) by JCSS Model Code. The assumption is that the impact energy does not exceed the critical impact energy value, i.e. the condition where the ultimate limit state of the barrier structure is just exceeded, i.e. $P(E_{imp} \geq E_{krit})$. The characteristic parameters define the ultimate limit state are the impact energy or the magnitude of the dynamic deflection of the barrier D_{dyn}.

The ULS is defined as the condition when the barrier loses its function, i.e. excessive dynamic deflection, breakage or overcoming of the barrier occurs during the impact. Due to the local conditions of the installation of the barrier, it is possible to modify the ULS criteria so that a dynamic deflection

D_{dyn} exceeding the design value is considered a sufficient condition. However, local conditions are considered, e.g., a bridge column, a barrier over a slope etc., where a higher deflection is not desirable.

Note: In case of the impact force determination, it is necessary to complete the probabilistic model with the vehicle stiffness variable. Obviously, this will complicate the model considerably.

In the following example, the vehicle stiffness is a feature of the NLDFEA model and could be defined as deterministic parameter. The procedure of road barrier reliability assessment is shown in Fig. 63.

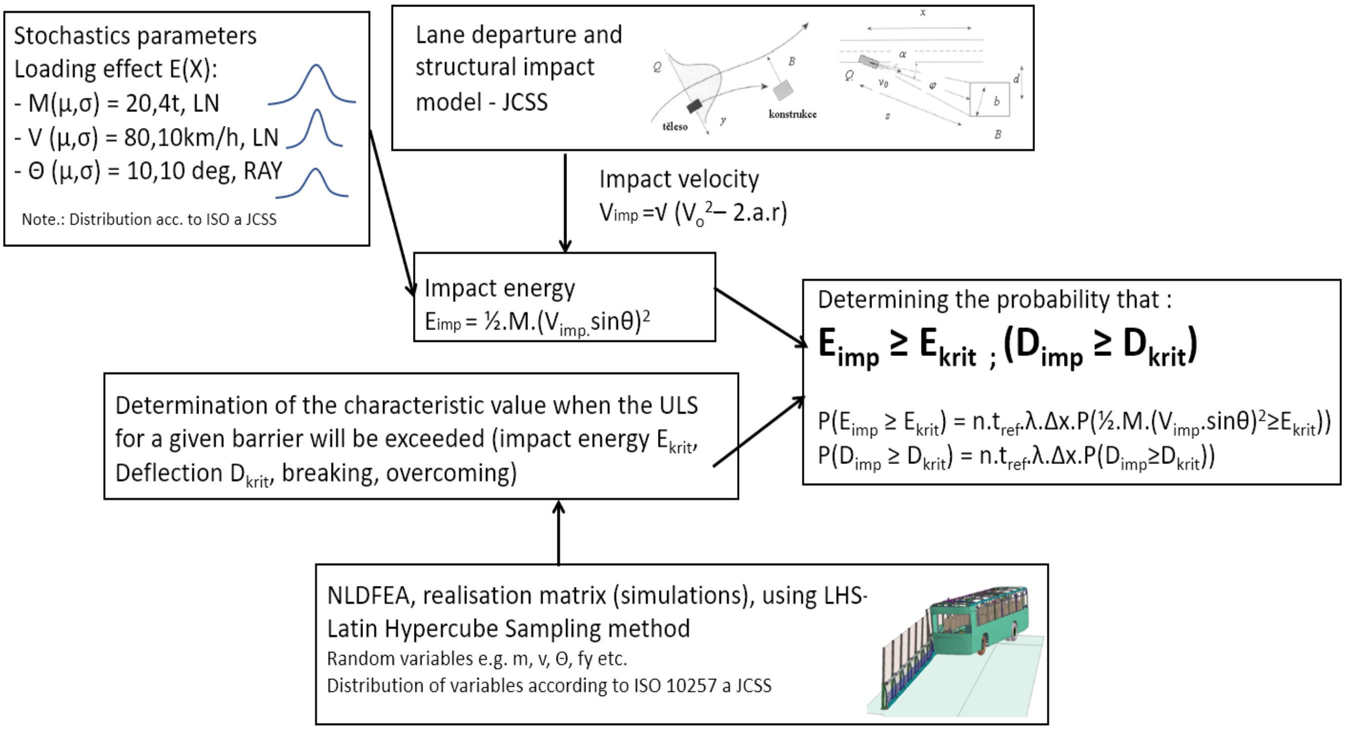


Fig. 63:Road barrier reliability assessment diagram – particular application for accidental impact loads

Three basic variables to describe the stochastic effects of accidental loads were defined: Mass of the impacting vehicle M, Impact velocity v and Impact angle θ.

To show the stochastic variables on the structural resistance side, we choose the ultimate strength of the barrier post and guardrail material fu [MPa]. For probabilistic models of material properties, normal, lognormal or Weibull distributions are usually used. If the characteristic value of a material properties and its variation coefficient are known, then the average $\mu(x)$ can be determined based on its characteristic value X_k and the variation coefficient V_x as:

$$\mu(x)= X_k/(1-2V_x) \qquad (38)$$

The probabilistic models for the load and resistance quantities of the structure are based on the recommendations of the JCSS and ISO 10252, see Tab. 18.

Tab. 18: Probabilistic models for the load and structural resistance quantities according to JCSS and ISO

Symbol	Description	Distribution	Mean μ	St. dev. σ	Notes
n	Number of HGV per day	Deterministic value	1/ day	--	Traffic intensity depends on local circumstances.
λ	Number of road leaving incidents per travel distance	Deterministic value	10^{-7} / km / year	--	--
Δx	Part of the road from where collisions may be expected	Deterministic value	100 m	--	--
m	Vehicle mass	Normal	20 ton	12 ton	--
v	Vehicle velocity	Lognormal	80 km/hr	10 km/hr	Velocity when the vehicle leaves the road.
a	Deceleration	Lognormal	4 m/s^2	1.3 m/s^2	Due to braking, terrain roughness, and obstacles.
φ	Angle between vehicle trajectory and road axis	Deterministic value	10°	--	Rayleigh distribution with $\mu = \sigma = 10°$ suggested in ISO 10252 and [3], [4].

To determine the impact energy E_{imp}, it is essential to determine the magnitude of the impact velocity v_{imp} , which is based on the JCSS probabilistic impact model. The vehicle slows down after the point of leaving the line due to terrain, obstacles or driver intervention. Then the impact velocity can be determined as:

$$v_{imp}(t) = v_o - a.t \qquad (39)$$

For uniform deceleration, the speed and distance r can be calculated as a function of time:

$$r(t) = v_o.t - ½\, a.t^2 \qquad (40)$$

After eliminating time, we get the velocity as a function of distance r:

$$V_{imp} = \sqrt{(v_o^2 - 2a.r)} \qquad (41)$$

$$r = \sqrt{d^2 + x^2} \qquad (42)$$

where x and d are the distances of the vehicle from the obstacle in the longitudinal and transverse directions. It is agreed that $x = r.cos\theta$

The deceleration a is recommended to be considered as a random variable with a lognormal distribution with a mean of 4m/s^2 and a variation coefficient of 30%. That means in 90% of the cases it can be assumed that the deceleration is between 2 and 7 m/s^2. The magnitude of the impact energy is therefore determined:

$$E_{imp} = ½ .m.(v_{imp}.sin\ \theta)^2 \qquad (43)$$

The value of the critical impact energy E_{krit} is determined by nonlinear dynamic simulations of the impact event where the ULS limit has been exceeded.

Note: If we choose the dynamic deflection D_{dyn} as the characteristic value, its magnitude can be determined from the simulations and further compared with original design value. It is important that any overrunning of the barrier or breakage of a main longitudinal member (guardrails) is classified as a failed result in accordance with EN1317 [7].

The realisations are generated by stratifying the uniform coverage of the domain by a specified number of realisations. The realisation matrix is generated simply by random substitution of the variable order. The structure failure probability, represented as exceeding the critical value of impact energy (or exceeding the dynamic deflection), can be given by:

$$P(E_{imp} \geq E_{krit}) = n.t_{ref}.\lambda.\Delta x.P(½.M.(V_{imp}.sin\theta)^2 \geq E_{krit})) \qquad (44)$$

where:
t_{ref} is considered time period
The meaning of other variables is shown in Tab. 18.

The failure probability function (44) does not include model uncertainties. It is advisable to consider in the limit state function the model uncertainties representing the basic variable related to the accuracy of physical or statistical model. Model uncertainties of the loading effect Θ_E influence the value of the impact energy E_{imp} and model uncertainties of the structural resistance Θ_R have impact to critical energy E_{krit}.

12.2 Probabilistic assessment of the road barrier structure - case study

To illustrate the probabilistic procedures for verifying the road barrier, an example from simulation case study 1 was considered, see chapter 8. It is a crash into a barrier designed for restraint level H2, i.e., a 13t bus crashing at 60kmh through an angle of 20 degrees. The impacting vehicle in this study is not the original testing vehicle but a standard 3-axle Tatra truck, see Fig. 64. In the context of this study, we will hence focus on one HGV impact, which differs from the testing vehicle, however its occurrence in regular traffic is quite high (and the probability of impact as well). We can assume that despite very similar impact energy, the actual impact will be quite different. Therefore, we should modify the input variables in the probabilistic models.

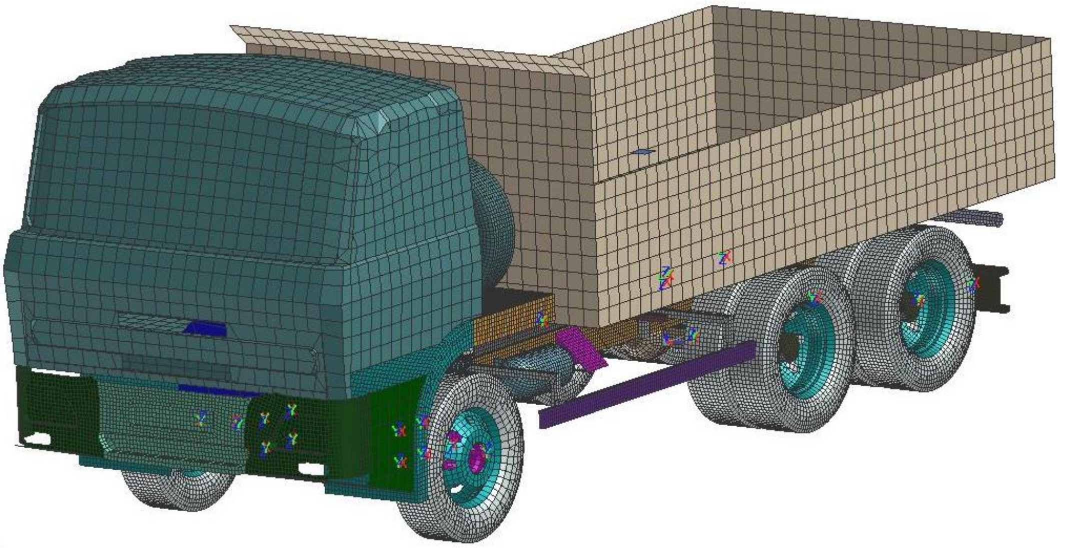


Fig. 64:Impact vehicle FE model used for road barrier probability assessment

For the vehicle mass we select the four-parameter Beta distribution (lower limit, *m*, *s*, *w*). The lower limit is determined by the minimum operating mass of the truck which is 12.2t. We assume an average weight of 22 tons, which is higher than the mean. This takes into account the tendency of trucks to ride fully loaded. We estimate the standard deviation as σ =3.5t and the skewness as *w*=-0.2. For other data, see Tab. 19. The distribution function is given in Fig. 65. There is a visible tendency for trucks to be loaded in traffic, confirmed by some other studies [26].

Fig. 65: Four parametric Beta distribution representing the mass of the vehicle

Tab. 19 shows the default probabilistic models of the random variables for the analysis, including the reference for background papers. The problem could be simplified considerably if some of the random variables become deterministic. In this case study, the magnitude of the deceleration after lane departure is defined as $2 m.s^{-2}$, which corresponds more to the deceleration due to rolling resistances, i.e., the vehicle is not actively braking. Next deterministic value is the 3m distance from the obstacle (barrier).

Tab. 19: Default probabilistic models of random variables

Variable	Distribution	Char. value X	Mean μx	St. dev. σx	Var.coeff Vx	Parameter 1	Parameter 2	Reference
Mass	Beta	--	22000 kg	3500 kg	0,159	Lower bound = 12 200 kg	Upper bound = 29 383 kg	1/Adaptation of ISO 10252 2/Report 291*
Velocity (highway)	Lognormal	--	80 km/h	10 km/h	0,125	μy =4,374	σy = 0.125	ISO 10252
Angle	Rayleigh	--	10 deg	5.23 deg	0,52	μy =5,23	σy = 7,981	ISO 10252
Yield strength	Lognormal	420 MPa	451,6 MPa	--	0,035	μy = 6,112	σy = 0,035	AHG Reliability**
Deceleration	Deterministic value	2 m/s^2	--	--	--	--	--	--
Distance	Deterministic value	3m	--	--	--	--	--	--

* Report 291-Ministry of Transport Denmark [26].

* * Draft Technical Report from AHG Reliability background - 2021-04, p. 119

Based on the initial values, we get a matrix of realisations. In our case using the LHS method (Latin Hypercube Sampling). We chose 20 realisations (i.e. 20 simulations). This is reasonably large enough samples to cover the entire design domain. The matrix of realisations is generated by randomly substituting the order of the variables, see Tab. 20.

Tab. 20: LHS output: case study realisation matrix

Simulation no.	Mass	Initial velocity	Angle	Yield Strength	Impact velocity	Impact energy
	[kg]	[m/s]	[rad]	[Mpa]	[m/s]	[J]
1	15091	24.77	0.0471	448	24.53	10084
2	16615	18.43	0.1278	434	18.10	44216
3	17614	24.23	0.0651	483	23.98	21453
4	18418	20.84	0.0566	461	20.55	12440
5	19114	17.28	0.1703	440	16.92	78668
6	19744	21.54	0.1576	429	21.26	109855
7	20328	26.38	0.2478	452	26.15	418181
8	20880	20.07	0.0205	470	19.77	1720
9	21409	22.94	0.0360	454	22.68	7143
10	21923	21.88	0.1193	446	21.60	72525
11	22428	22.22	0.1036	466	21.95	57757
12	22928	20.47	0.1368	421	20.17	86751
13	23429	19.11	0.0960	459	18.79	37991
14	23937	23.75	0.0809	450	23.50	43155
15	24459	21.19	0.0732	463	20.91	28568
16	25003	19.63	0.0885	442	19.32	36416
17	25583	23.33	0.1113	437	23.07	84049
18	26222	25.45	0.1466	456	25.21	177792
19	26971	28.15	0.2077	444	27.93	447180
20	28003	22.58	0.1861	475	22.31	238446

It is very important to eliminate or confirm the mutual dependency of the variables. This can be shown in the correlation matrix, see Tab. 21. It can be assumed that the variables are sufficiently independent if the correlation coefficients are within +/- 0.5.

Tab. 21: Correlation matrix of independent variables in the case study

	Mass	Velocity	Angle	Strength
Mass	1	0.25	0.31	0.06
Velocity	---	1	0.29	0.19
Angle	---	---	1	-0.32
Strength	---	---	---	1

The result of a series of simulation calculations according to Tab. 20 is the determination of the dynamic deflection D_{dyn} , or other parameters defining the ULS excess (overcoming of the barrier, breakage of the main longitudinal element, etc.).

Tab. 22: Output of the case study simulations

Simulation no.	Dynamic deflection D_{dyn}	Barrier overcome	Failure	ULS exceeded
	[m]	[Y/N]	[Y/N]	[Y/N]
1	0,075	N	N	N
2	0,25	N	N	N
3	0,14	N	N	N
4	0,08	N	N	N
5	0,45	N	N	N
6	0,5	N	N	N
7	Failed	N	Y	Y
8	0,03	N	N	N
9	0,05	N	N	N
10	0,37	N	N	N
11	0,31	N	N	N
12	0,41	N	N	N
13	0,195	N	N	N
14	0,262	N	N	N
15	0,152	N	N	N
16	0,20	N	N	N
17	0,45	N	N	N
18	**0,81**	**N**	**N**	**Y**
19	Failed	Y	N	Y
20	**0,88**	**N**	**N**	**Y**

As is shown in Tab. 22, in 10% of the impacts, the barrier is overcome. This can be considered as a total failure of the structure. In this case it is always a non-compliant state. In the remaining cases, there is no overcoming of the barrier. Thus, we get a statistical set of dynamic deflection results with a total of 18 samples. Further the main statistical characteristics of the set (number of measurements, mean, variation coefficient, skewness, minimum and maximum values) were determined. Finally, we make a histogram with the distribution of relative frequency into 6 classes.

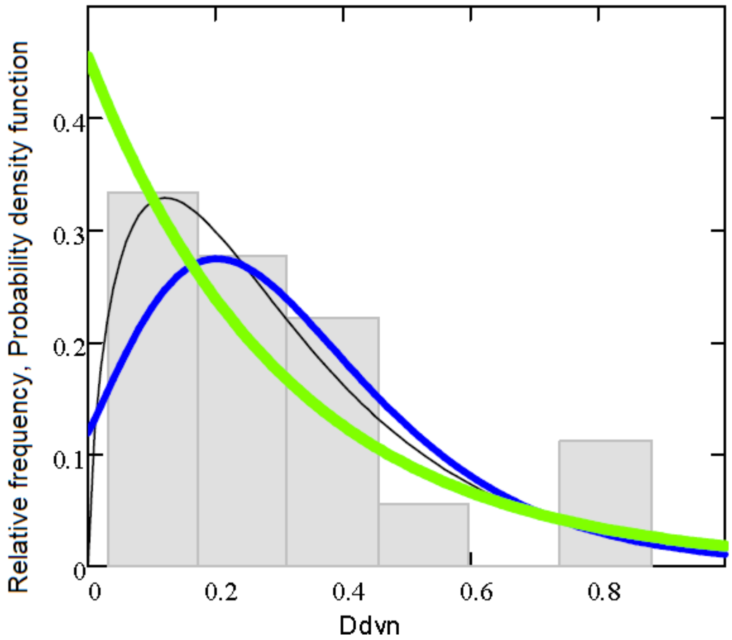


Fig. 66:Histogram of statistical results D_{dyn}

From the case study showing the probabilistic assessment procedures, the following conclusions are formed:

1. Simulations result in LHS indicate that the barrier collapses and the vehicle is not retained in 10% of all accidental loading cases.

2. For the remaining 90% of cases:

2a. Statistical moments of $D_{\mathrm{dyn,model}}$ are estimated with regards to LHS simulation results as mean μ = 0,31 m; variation coefficient V = 78% and skewness ω = 1,11

2b. Actual dynamic deflection of the barrier D_{dyn} is estimated as $D_{\mathrm{dyn}} \approx \theta \,.\, D_{\mathrm{dyn,model}}$

3. Model uncertainty coefficient were defined in the thesis (see tab.19 for case study no.1) where maximal difference D_{dyn} between the simulation and real test was -3,5%. Therefore, the model uncertainty coefficient is θ =1,04. The model uncertainty characteristics θ were estimated an example assuming: Mean $\mu\theta = \mu \,.\, \theta$ = 1,04 ; Variation coefficient $V\theta$ = 0,1; Skewness $\omega\theta = 3V\theta$ = 0,3.

3a. The statistical characteristics of D_{dyn} become μ = 0,32 m; V = 79%; ω = 1,14

4. Probability of the failure, $P(D_{\mathrm{dyn}} > 0{,}8\ m)|_{accidental\ truck\ impact}$, is then estimated as:

$0{,}1 + 0{,}9 \times P(D_{\mathrm{dyn}} > 0{,}8\ m) \approx 0{,}1 + 0{,}9 \times [1 - FLN(0{,}8;\ \mu = 0{,}31\ m;\ V = 79\%;\ \omega = 1{,}14)] =$

$0{,}1 + 0{,}9 \times [1 - FLN(0{,}8;\ \mu = 0{,}31\ m;\ V = 79\%;\ \omega = 1{,}14)] = 0{,}14$

5. $P_f = 0{,}14$ (given accidental impact) corresponds to reliability index of 1,1 which could be a reasonable reliability level for the safety barrier exposed to impact of the heavy truck.

12.3 Probabilistic model of the road barrier impact test loading

The procedure of the road barriers probabilistic assessment has no limitation to ordinary traffic impact situations only. It can also be applied to the probabilistic assessment of a road barrier impact test, e.g. according to EN1317. This approach, unlike other methods, provides the designer with essential information about the reliability margin of the structure in the required impact test. In other words, to specify, what is the probability of successful test result?

In this case, the probabilistic assessment approach is based on the method illustrated in the previous example, so we only use a different input parameter in the probabilistic models. Mainly, the loading effects values. The impact velocity, mass and angle are defined in the EN1317-2, including their tolerances in test. Unlike the previous case, the probabilistic models are taken from ISO 10252. The distribution basis values (*m,x,s,V*) correspond to the test conditions, see Tab. 23.

Tab. 23: Initial probabilistic models of the road barrier loading by impact test- application for H2 restraint level

Variable	Test tolerance in EN1317	Distribution	Mean μ	Standard deviation σ
Vehicle mass	12600 -13400kg	Normal	13 tons	0,3 ton
Vehicle velocity	69,3 -75,6kmph	Lognormal	60 km/h	1 km/h
Impact angle	19,8 – 20,8deg	Normal or Deterministic	20°	-

The further process is a variation of the previously described procedure. However, in this case we should consider a several circumstances:

- The crash test probabilistic model does not consider the model of the vehicle lane leaving and collision into the obstacle by JCSS (see section 3.7.). In case of the crash test, the probability of impact is equal to 1. The speed and angle are kept under control until the very last moment before impact and therefore are not affected by braking or other drivers’ interventions.
- When selecting the probabilistic models, it is necessary to take into account the test technology being used - e.g. the technology how the vehicle is being guided towards the barrier and its effect on the impact angle.
- The definition of the ultimate limit state of the barrier in this case is only through the dynamic deflection value D_{dyn}. Exceeding the design value D_{dyn} is considered as failing. An adaptation of the ULS criteria to the particular conditions is not recommended.

The output of the assessment will be the probability that the structure can withstand the load of the impact tests without exceeding the design value D_{dyn} or overcoming the structure or breaking of crucial parts, mainly the longitudinal guardrails.

13 Application to bridge pier impact force analysis

Last part of the thesis aimed to apply the approach from above to analyse the accidental situation, when LGV or HGV impact to bridge pier. And, of course, there are no principal limitations to broaden the analysis to another potential objects in the road or bridge vicinity, e.g. lightings, rails, traffic signs and buildings etc. Then simulation impact force (means the contact force between the vehicle and structure) is proposal for worst case design force, because the design force of vehicular impact provided by EN1991-1-7 and ISO 10252 seems to be underestimated.

Typical example of the accidental impact leads to significantly higher forces (from 3 to 5 times). Thus, appropriate safety measures to reduce the impact force should be applied. Today, most bridge piers are protected by road barriers. The question arises, whether impact force will be reduced, if road barrier is installed in front of the bridge pier.

Further in case studies, the recommendations in the TP114 (applicable to the Czech Republic) are considered. TP 114 recommends using the road barrier with minimum restraint level H2 (Bus 13 tons impact, 70kmph, 20deg) to protect the bridge piers and the portals. The distance between the road barrier guardrail and the bridge pier is recommended at least as the working width *W*. However, this distance is not mandatory and may be theoretically any, e.g. 10 cm only. The distance between the bridge pier and road barrier is also analysed in case study.

Note: Where and how to install a road barrier, including geometric conditions, is solved by individual countries themselves within their National Annexes or executive regulations.

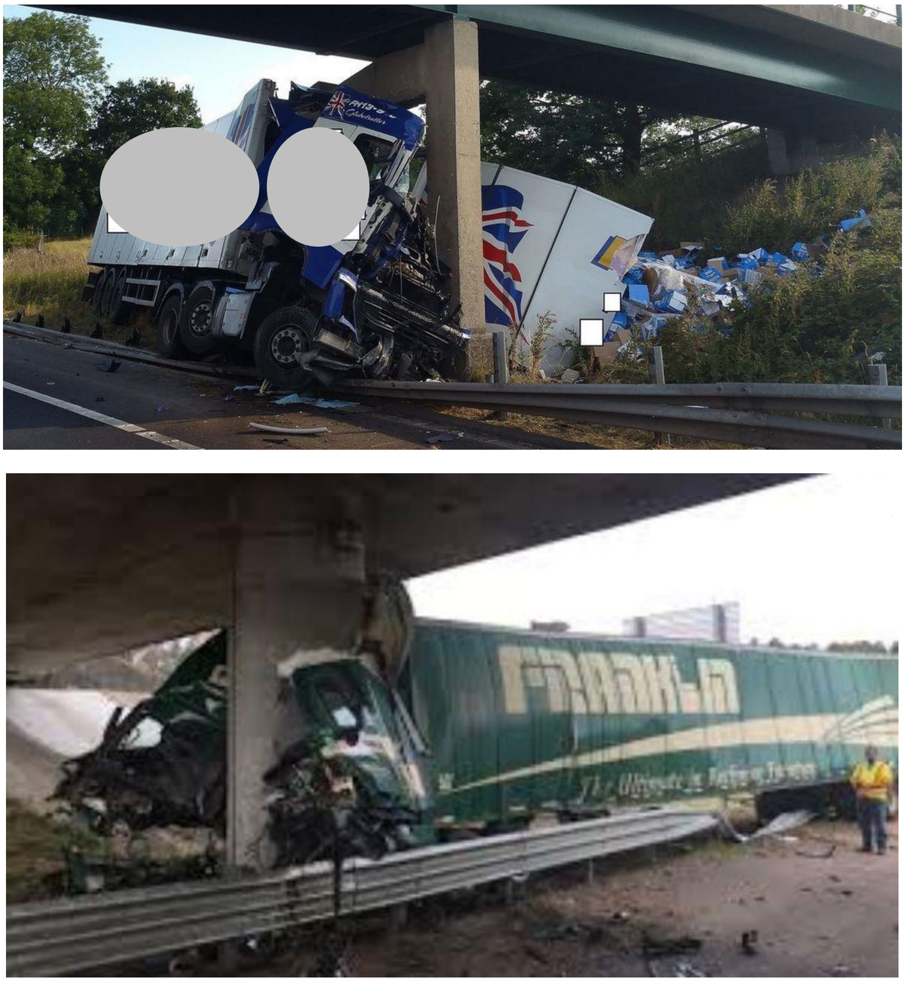


Fig. 67:Accidental LGV impacts into the bridge pier protected by road barriers – illustration figures, source: google public available pictures

Accidental impact by LGV into the bridge column

Let's have a look at case when impact exceeds the ultimate limit state and road barrier fails due to any reason discussed above. In this case vehicle likely overcome the road barrier and continue in its direction (or slightly changed direction) outside the road. Then crash into the obstacle in the road vicinity. Unfortunately, this situation leads very often to serious accident with serious injury and fatalities, as it is shown in Fig. 67.

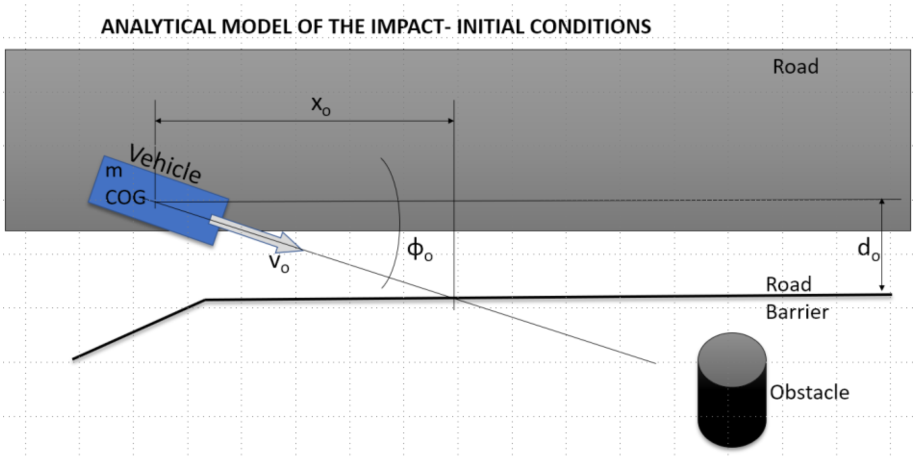
Analytical modelling of the LGV impact crash event

Analytical modelling of this accidental situation is described on the time sequence in Fig. 68. Overall crash event is divided into 5 main phases. Then each phase is solved individually. Previous phase output is further used as initial conditions for next phase.

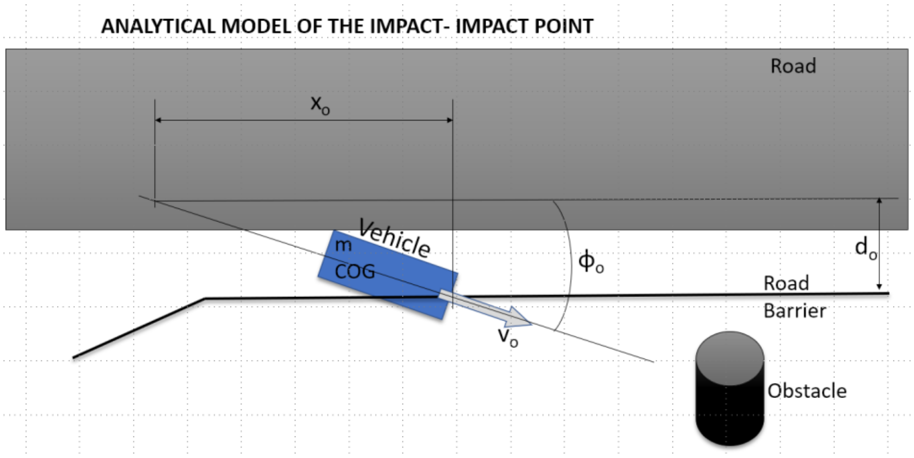
In analytical approach we can use the theories given in sections *3.3." Eurocode dynamic force application"* and *3.4."Energetic approach"* . There are main crash milestones below:

- Phase 1 – Initial conditions: To define initial conditions the probabilistic model of the vehicle lane leaving and collision into the obstacle by JCSS is proposed, see section *3.7." Eurocodes and JCSS probabilistic impact model"*. The obstacle is represented by road barrier. Initial conditions are displayed on the Fig. 68a.
- Phase 2 – Impact point. Vehicle just gets in contact with the road barrier. Vehicle crashes with impact angle φ_0 and velocity v_0, see Fig. 68b.
- Phase 3 – Road barrier overcame. Road barrier deformation capacity cannot fully absorb the impact energy imposed by the LGV. There are several possible impact scenarios, which depend on the impact conditions and structural resistance. In our worst case the impacting vehicle overcomes the road barrier and continues in movement, as is shown in Fig. 68c.
- Phase 4 – After overcoming. Vehicle continues in its movement with different impact angle φ_1 and reduced velocity v_1, see Fig. 68d. Vehicle decelerates over the $x_1/\cos\varphi_1$ distance, with average deceleration a_2.
- Phase 5 – Impact to obstacle. Vehicle hits the obstacle with impact angle φ_1 and impact velocity v_2. Situation is shown in Fig. 68e.

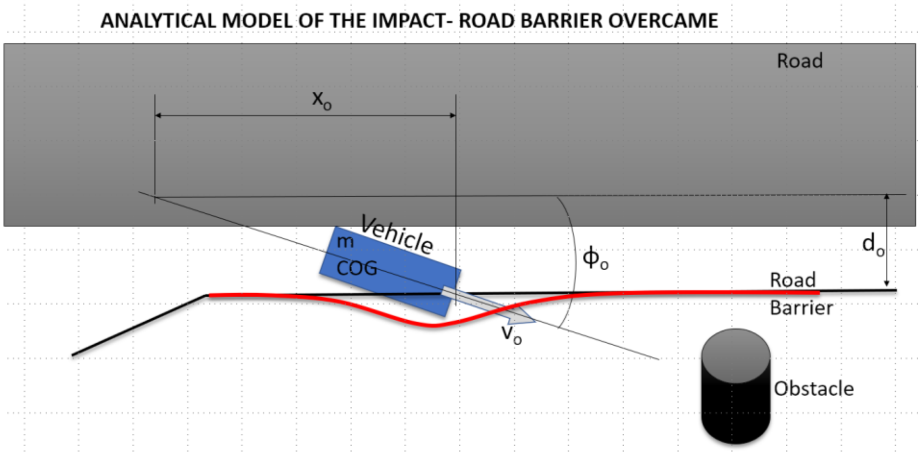
a/


ANALYTICAL MODEL OF THE IMPACT- INITIAL CONDITIONS
Road
x_o
Vehicle
m
COG
v_o
ϕ_o
d_o
Road
Barrier
Obstacle

b/


ANALYTICAL MODEL OF THE IMPACT- IMPACT POINT
Road
x_o
Vehicle
m
COG
ϕ_o
d_o
Road
Barrier
v_o
Obstacle

c/


ANALYTICAL MODEL OF THE IMPACT- ROAD BARRIER OVERCAME
Road
x_o
Vehicle
m
COG
ϕ_o
d_o
Road
Barrier
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Obstacle

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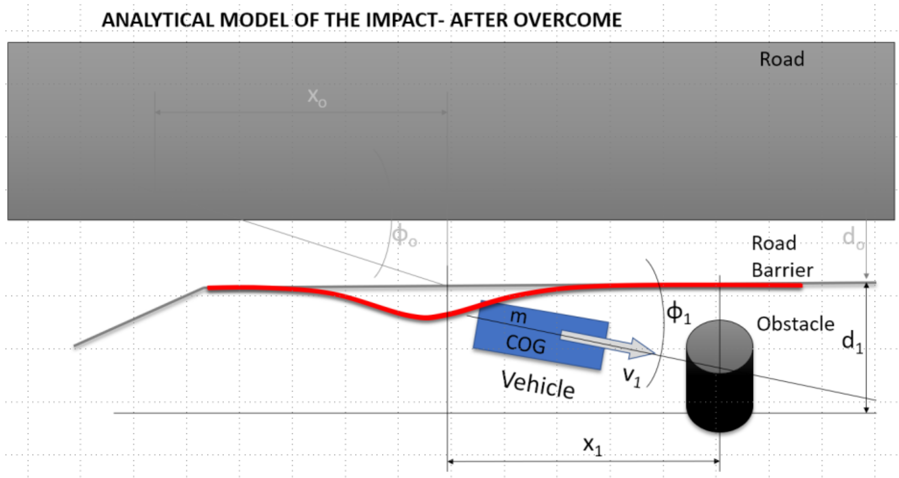

e/

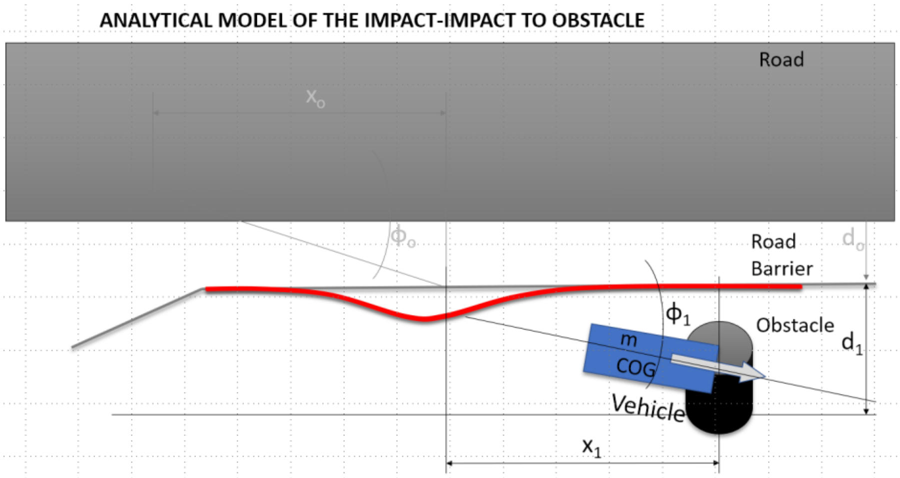

Fig. 68:Analytical model of the accidental HGV impact into the bridge pier protected by road barriers

The analytical approach weak point is to determine whether the barrier would be overcome under the given input conditions (phase 3). This can only be determined very simply, for example by determining the stress in the main longitudinal member of the barrier (guardrail), determining the deflection line of the barrier, etc.

However, this estimate will always be very inaccurate and possibly misleading. Due to this inaccuracy, the determination of the vehicle movement parameters after overcoming the barrier (mostly the impact angle φ_1 and reduced velocity v_1) may be distorted.

13.1 Impact force to unprotected bridge pier – case study

Case study objective is to analyse the design forces imposed by LGV impact into unprotected bridge pier. Bridge pier impact isn’t normative mandatory type of the impact. Therefore, the aim of the case study is to determine the maximal contact force, expected in the real operation. Initial conditions are different comparing to the road barrier crash test (particularly H4b). The impact energy is more than 150% of the original road barrier crash test (724,5 kJ vs. 1096,6 kJ). Impact scenario was chosen to get the baseline model for further road barrier performance analysis, mainly in term of the impact force reduction using a road barrier protection.

FE simulation

FE model consists of the bridge structure supported by C45/50 concrete circular pier with 1 m diameter and 6 m height. The bridge structure is represented by mass structure (not rigid) firmly supported at both ends. Impacting vehicle (LGV with initial conditions of m = 30 t, stiffness k and impact velocity v=80 kmph) consists of the deformable parts in frontal and side area.

Overall view on simulation model is displayed in Fig. 69.

Unlike modelling of the road barriers impact, the effect of vehicle stiffness is main decisive factor to analyse the impact force and its course. However, data of the trucks and buses stiffness are not public available. Thus, in case study three levels of the truck cab stiffness were chosen to illustrate the vehicle stiffness effect.

Vehicle hits the column just in the middle of the frontal part of the cab. However lateral offset before the crash (how the vehicle hits the bridge pier) also significantly affects the contact force. Initial offset position analysis is not a part of the work. Details can be found in [27]. Final state of the simulation and residual deformation of the column is shown in Fig. 71.

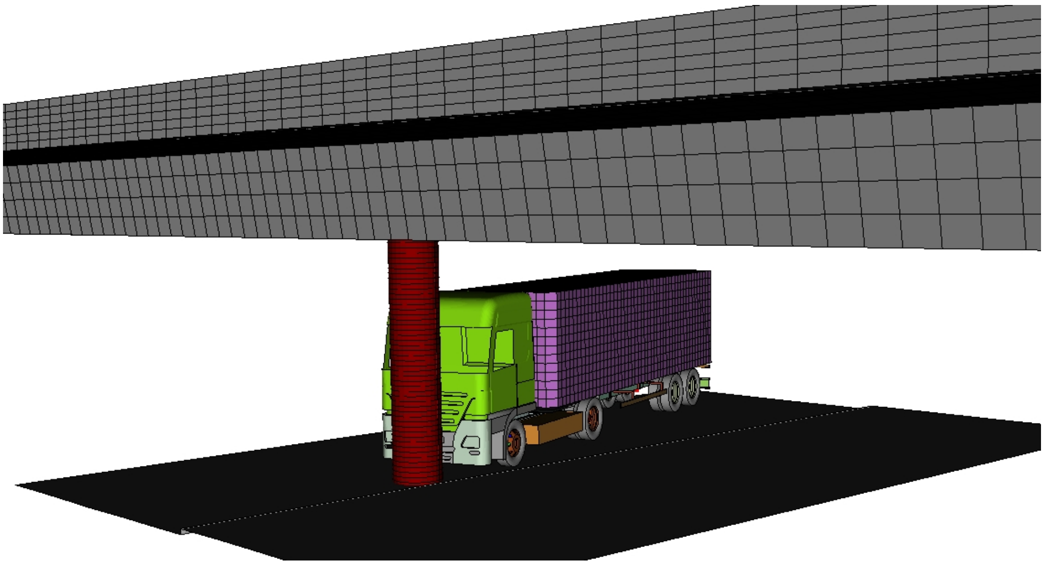

Fig. 69:FEA simulation of the accidental situation – initial state

Results discussion

Assessment of the simulation results are based on two main indicators, *vehicle – bridge pier contact force* and *pier deformation*. *Vehicle- bridge pier contact force* in the simulation represents the accidental design force in EN1991-1-7. In FE simulation is advisable to evaluate the contact force time history over entire crash event. Therefore, the comparison with pure design value from Eurocode or result of the analytic calculation could be slightly misleading.

Simulation results show the direct link between the vehicle stiffness and contact force time history. Different vehicle stiffness (mainly the vehicle cab in our case) finally leads to different contact force time history as shown in graph in Fig. 70.

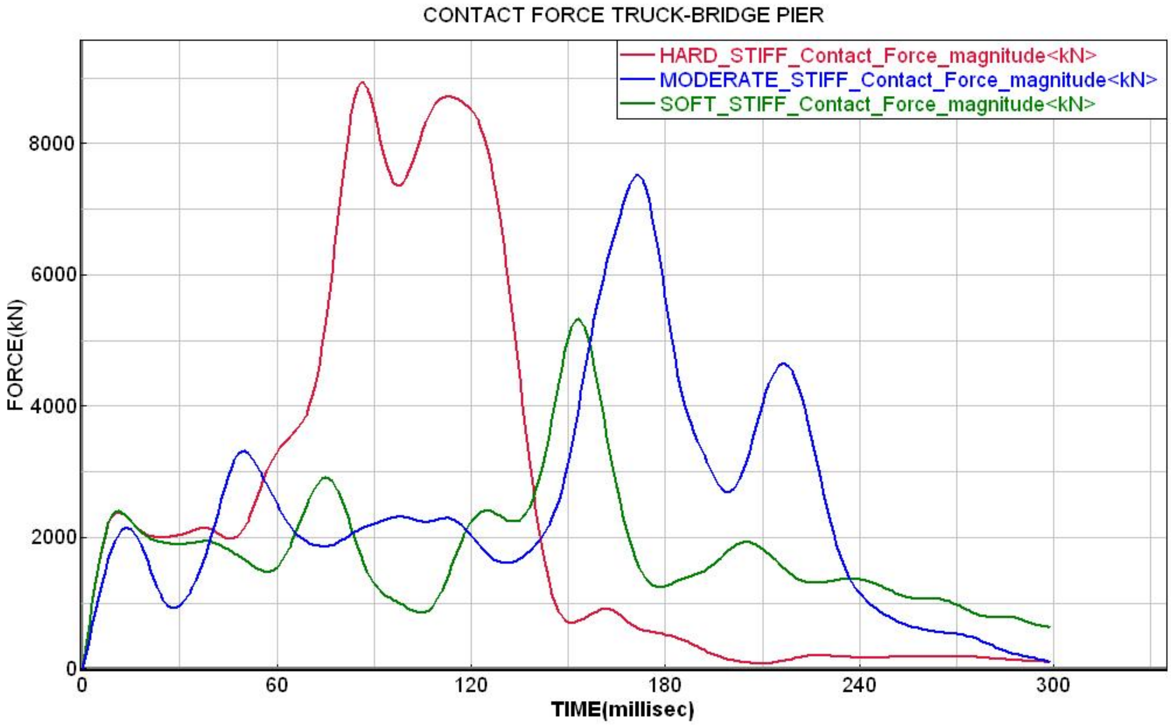

Fig. 70:Contact force time history for different vehicle stiffness (Hard – Moderate – Soft)

The average value of the contact force for a soft vehicle (corresponds with the Eurocode premises) oscillates around 2000kN, with peak values app. 3000 - 5000 kN. Vehicle model complexity affects the maximal contact force peak. These values were compared with the design force recommended in EN1991-1-7 for accidental situation. Final state of the simulation in 350ms with residual deformation of the column is shown in Fig. 71.

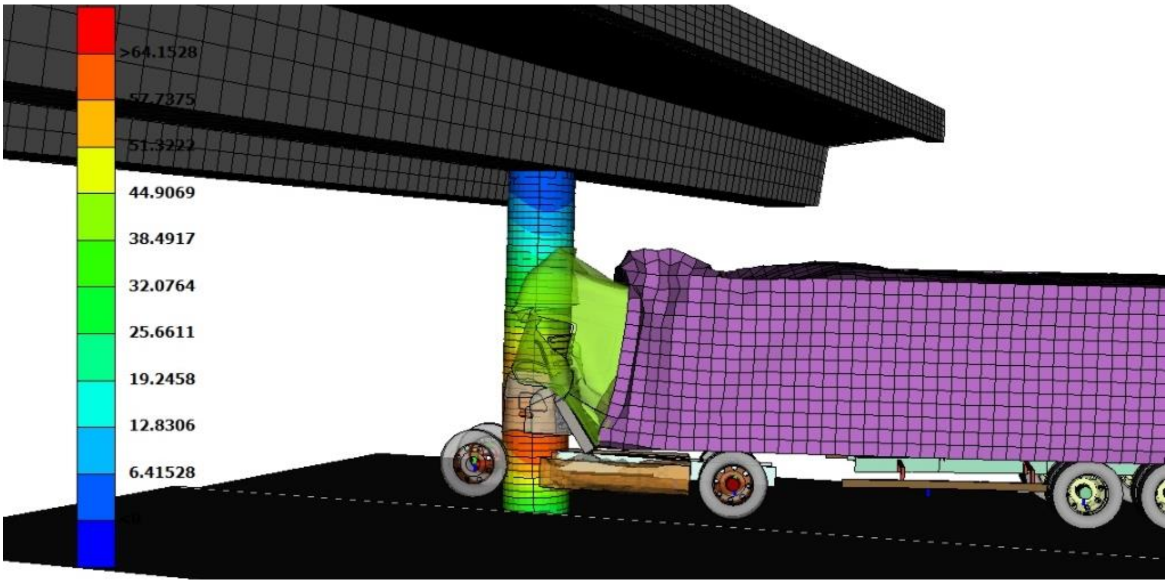

Fig. 71:Bridge pier impact force FEA simulation (no road barriers). Deformation scale in mm

Deformation of the bridge pier was also evaluated in all case studies, even if has no significant effect to the Contact force value. Bridge pier deformation (in maximal bending point) is 260/59/24 mm for Hard/Moderate/Soft vehicle simulation.

13.2 Impact force to bridge pier protected by road barrier – case study

The issue of accidental design forces arises from LGV impact to bridge pier protected by road barrier which could be considered as a complex problem. The impact force value may considerably vary, depends on many circumstances (comparing to the road barrier crash). If we omit the initial conditions (e.g. vehicle mass, impact speed and angle), the local geometrical conditions are also crucial and finally define the impact severity. In order to estimate the maximal impact force in real operation, possible accidental worst case (LGV, 80kmph, 30tons) was taken into account.

Last case study deals with the impact into bridge pier protected by road barriers. Models are based on previous example in term of the initial conditions, impact vehicle and obstacles. Two different road barriers protecting the bridge pier were considered. Both structures were taken from crash simulation case studies, see section *8-Simulation of the selected crash test scenarios*. The restraint level for road barrier no.1 is H2 (minimal allowed level) and H4b for road barrier no. 2. The distance between the bridge pier and road barrier back side could play a role to minimise the impact to the bridge pier. Therefore, five distances are considered in analysis. The distance of the bridge pier from the road barrier in perpendicular (+Y) and longitudinal (-X) direction is shown in Fig. 72. Initial state of the simulation is also shown in Fig. 72. The geometric proportions of the model are based on real data, as it is defined in [9].

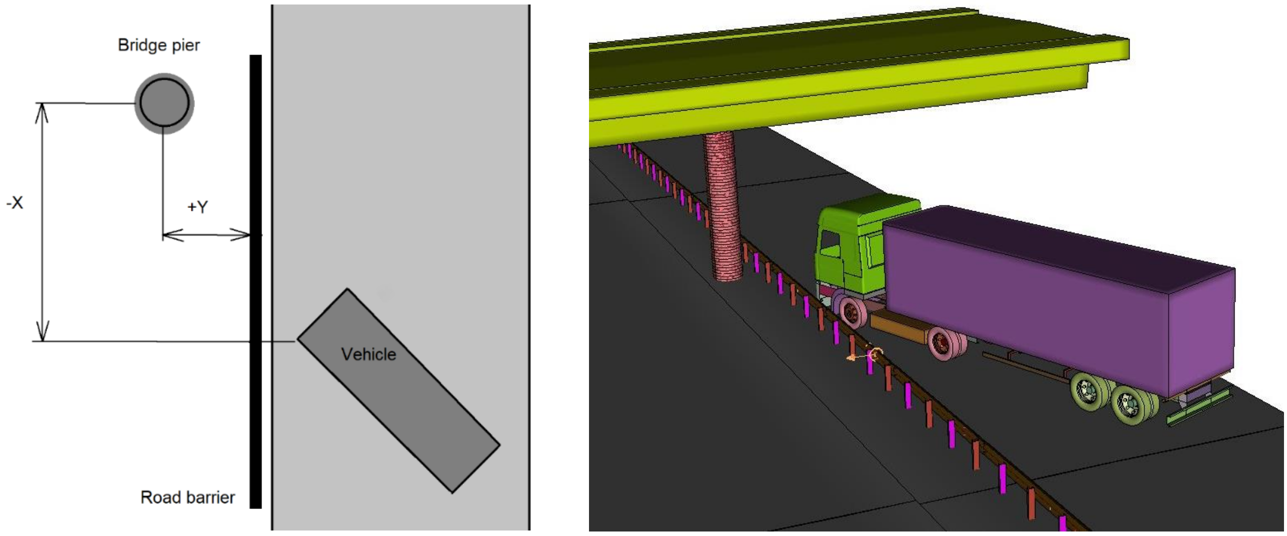

Fig. 72:Bridge pier case study geometrical situation

It is obvious, that road barrier H2 cannot withstands so hard impact imposed by LGV with mass app. 30tons and impact speed of 80kmph. Vehicle likely overpasses the road barrier with typical consequences. In this extreme case, where the pier protection is not sufficient, the impact force is almost identical to unprotected piers - see section 10.1.

13.3 Evaluation of the bridge pier analysis results

The most effective reduction of possible impact force is given by the road barrier H4 protection. Simulations show that impact force value in this case reach up to 2900kN. It is still app. 3 times higher than accidental impact force given from EN1991-1-7. The result of initial and maximal peak of the impact force with regards to the pier distance is shown in Tab. 24.

Tab. 24:Pier impact force peak (initial/ maximal) value for different pier distance

Pier-barrier distance (+Y)	RB type 1 – H2 (initial/ maximal)	RB type 2 – H4b (initial/ maximal)
0mm	750/1800 kN	1000/1000 kN
200mm	1400/7000 kN	1450/1850 kN
400mm	1600/2200 kN	1100/1100 kN
600mm	1800/5400 kN	1600/2900 kN
Acc. to crash test*	1400/1400 kN	1550/2500 kN

*"Acc to crash test" means that pier distance is equal to dynamic deflection *D* of the road barrier measured in the real physical crash test, accordingly to the proposal in TP114 [9].

The impact force time history provides overall view on crash event. The complete impact force time history for road barrier type 1 is shown in Fig. 73. The graphs below represent the global overview of all simulations with respect to the bridge pier offset and pure impact to unprotected bridge pier.

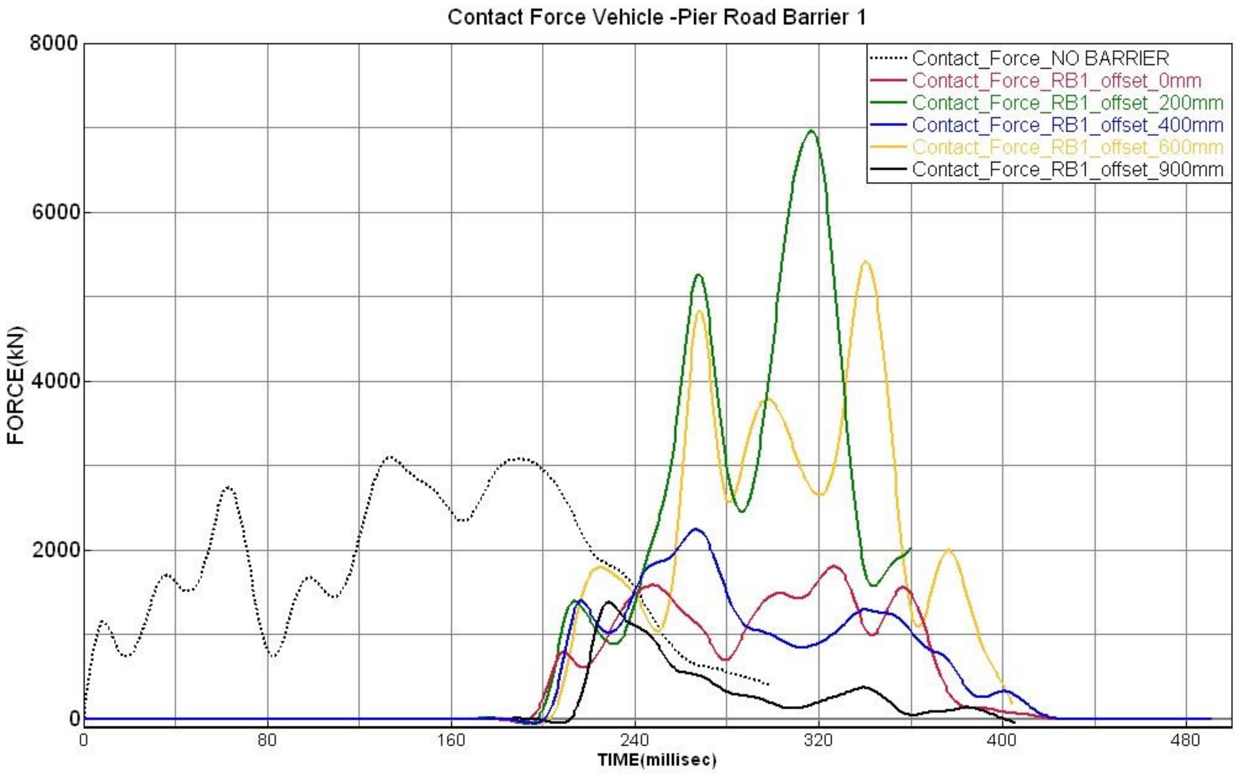

Fig. 73: Bridge pier impact force for road barrier of type 1 and different distance from bridge pier – overall view

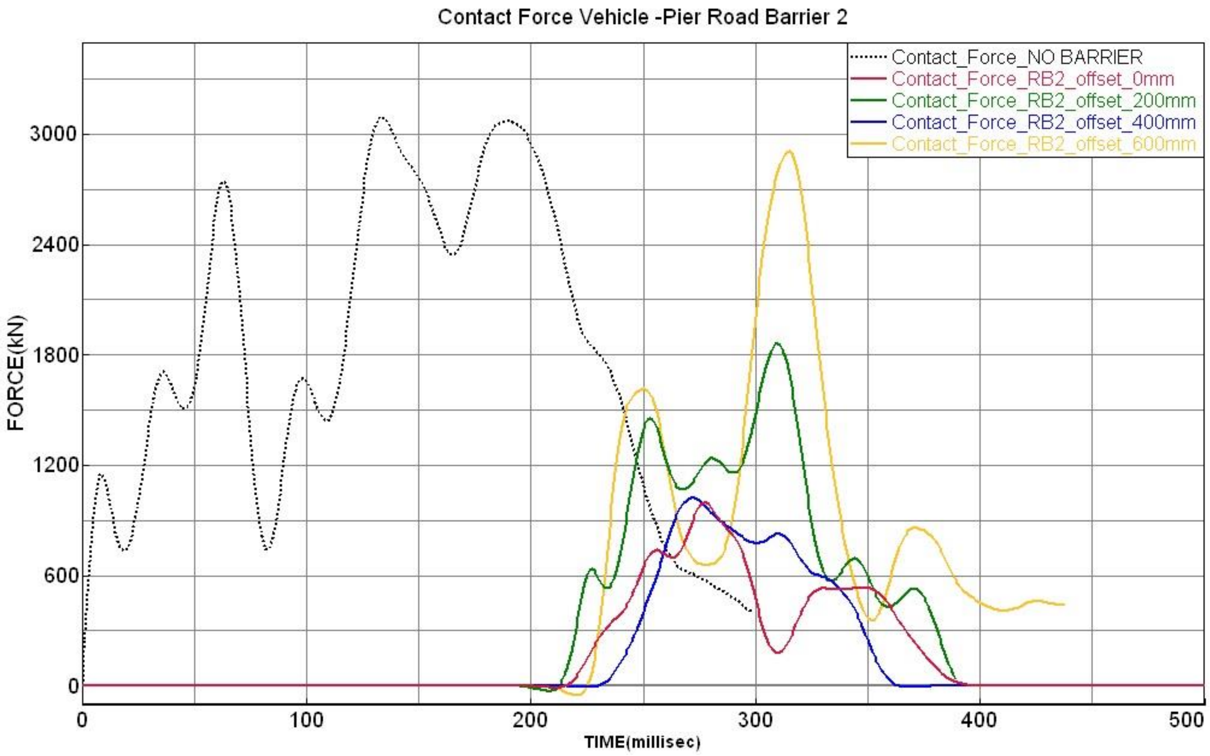

Fig. 74: Bridge pier impact force for road barrier of type 2 and different distance from bridge pier – overall view

All impact force curves indicate the similar features. There is an initial force peak just in the first contact with bridge pier and secondary peak in the middle of impact. While initial peaks have almost the same values, the secondary peaks (see maximal peak in Tab. 24) seems to be very sensitive to geometrical conditions of the impact (after initial phase of the crash) and vehicle model complexity.

13.4 Impulse of the bridge pier contact force

To complete the analysis results from previous section, it is necessary to provide a different view on the bridge pier deformation. The bridge pier subjected by the LGV impact is loaded over the time course of the impact force rather than by a simple peak force alone.

Maximal peak of the contact force represents a simple and comparable parameter. However, impulse of the contact force provides more complex view on the bridge pier load. The contact force impulse is purely integrated from contact force time history.

Course of the contact force and their peak values may look very different for given impulse force (N.s.). Relatively low contact force value with long time exposition could be dangerous for structure more than high force peaks with short exposition in range of milliseconds only.

In the Fig. 75 the integral values resp. force impulse of all simulation variants incl. unprotected bridge pier impact is shown. Maximal impulse force value for particular impact scenario is given by unprotected bridge pier impact – see black dash curve in Fig. 75 and Fig. 76. Also, the bridge pier offset (lateral distance from the road barrier) is considered in graph.

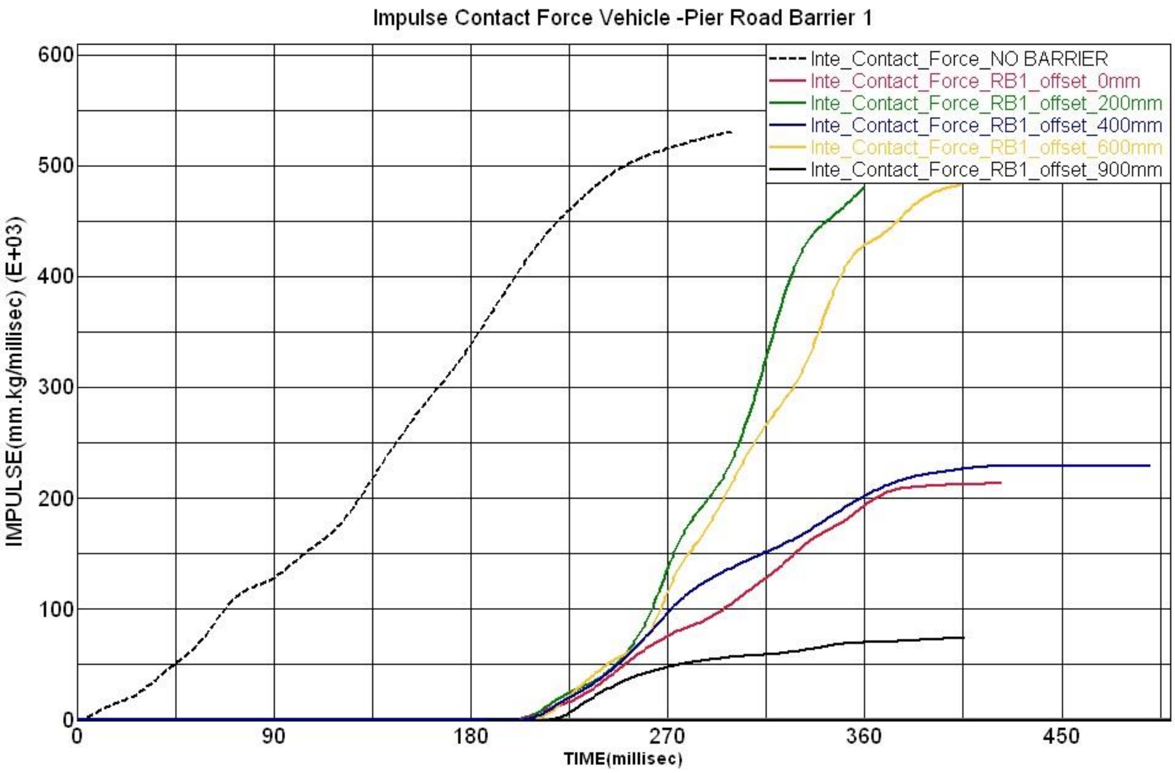

Fig. 75:Impulse force (time integral) for Road barrier 1 and unprotected pier impact

The difference in absolute values between the unprotected impact (black dashed curve) and the rest of curves represents the impact energy absorbed by road barrier (dissipated into the barrier deformation) before the vehicle impact to the bridge pier.

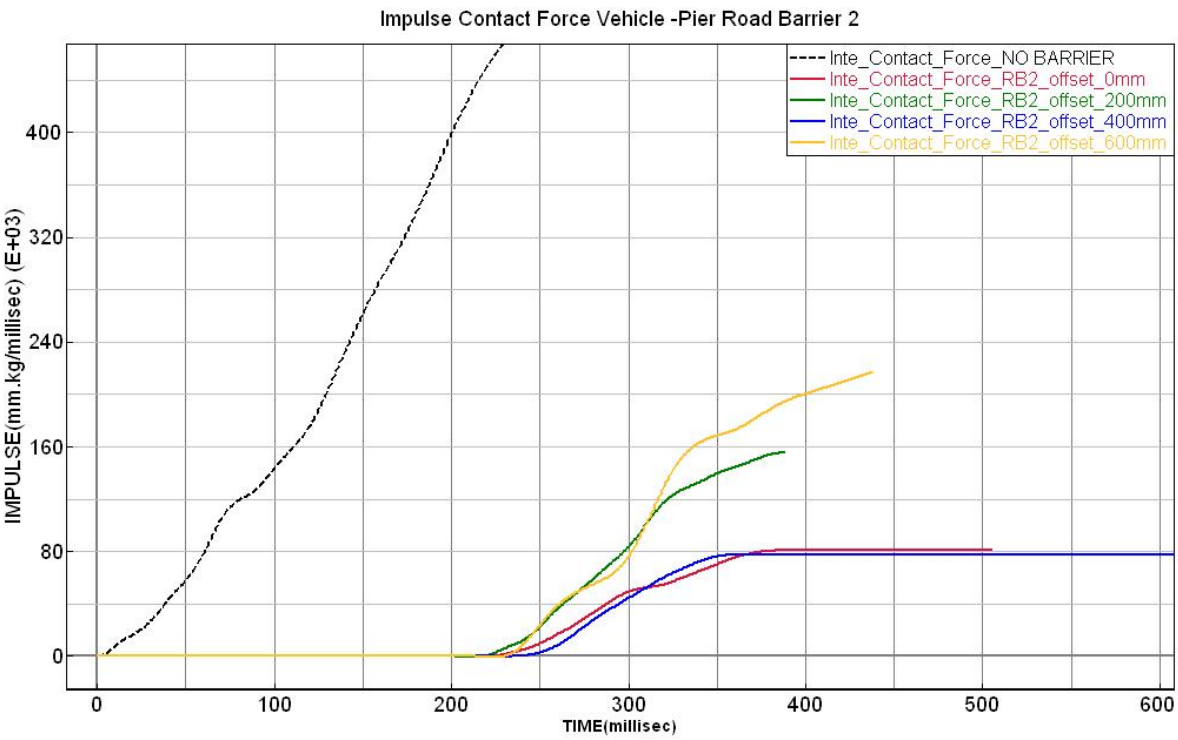

Fig. 76:Impulse force (time integral) for Road barrier 2

13.5 Probabilistic assessment of bridge pier impact force.

Last example of the probabilistic assessment application is the analysis of the impact force into the bridge protected by road barrier. The probabilistic model is based on the concept illustrated in case study, see section 12.2.

When building a probabilistic model, we determine the stochastic variables and purely deterministic values. It is not possible to consider all values as stochastic (although this is actually true), as this significantly increases the complexity of the model. The following parameters can be assumed as deterministic parameters of the model:

- Geometrical impact conditions:
  - distance of the pier from the barrier
  - diameter of the column
  - position of the vehicle (excluding the angle of impact)
- Road barrier design is fixed.
- Impact vehicle design

Stochastic model values defined with regards to case study in section 12.2:

- Impact angle
- Impact velocity
- Mass of the impacting vehicle

The analyses can be completed by probabilistic models of the structural resistance, i. e. concrete strength, depths of the barrier posts, strength limits of the barrier, etc.

The initial impact conditions in the model are determined from the lane departure and obstacle impact model (see section 3.7). Also, the loading effect in the probabilistic model is identical to case study, see section 12.2. The structural resistance effect consists of two mutually independent structures: the protecting structure (the road barrier) and the protected structure (the pier).

The probability of the protecting structure failure, as the exceeding of the critical value of the impact force F_D, can be expressed by:

$$P(F_{\mathrm{imp}} \geq F_D) = n.t_{\mathrm{ref}}.\lambda.\Delta x.P(\tfrac{1}{2}.M.(F_{\mathrm{imp}} \geq F_D)) \qquad (45)$$

Also, the failure probability function (45) does not include model uncertainties, defines the accuracy of physical or statistical model. It is recommended to complete the function with the model uncertainty coefficients.

The rest of the procedure is very similar to case study in section 12.2. The output of the assessment is the probability distribution of the peak or characteristic value of the impact force, or the probability that the impact force F_{imp} will not exceeds the design force F_D.

14 Thesis conclusions and answers to research questions

14.1 Conclusions of the road barrier analysis and reliability assessment

The general thesis aim is to improve the theoretical models of the road barriers impact to be as close as possible to the physical crash tests. Thesis also aims to involve the probabilistic approach with support of nonlinear dynamic numerical simulations to assess the road barriers under accidental impact.

It should be noted that the aim of this work is not to substitute the physical testing of road barriers by numerical simulations (which would be honestly a very ambitious goal), just the opposite, to provide a comprehensive potential of computational methods in order to support the innovations in design and physical testing.

Application of probabilistic methods for the reliability assessment of road barriers gives a new perspective on the problem of selection and dimensioning of structures in the vicinity of the roads. The probabilistic methods allow to estimate the behaviour of the structure in real operation, to determine the margin of the structure in a crash test, or to verify the modification of the barrier design. This information can be used by the designer in final design development or e.g., to detect the weak points in the structure that would not be apparent in the crash test.

Next, the conclusions of the thesis are summarized as they correspond to the research questions given in introduction.

1/ Refinement of the ultimate limit state (ULS) definition for road barrier structures.
In the first part of the work, the methodology for the analytical calculation of accidental impact event was introduced. Ultimate limit state is a key evaluation parameter in analytical approach to assess safety performance of road barriers. Since ULS wasn’t directly considered in the standardised requirements for the road barriers verifications and described yet, the thesis proposes the ULS definition. Two different ultimate limit states for LGV (Large goods vehicle) and HGV (Heavy goods vehicle) impact and passenger car impact are considered.

2/ Proposal of the virtual simulation method that reflect all features of real physical crash tests.
The thesis presents three different approaches to analyse the RRS(Road Restraint System) crash event.

- Static analysis of the RRS loaded by equivalent static force.
- Multi body approach of the RRS crash with non-deformable parts.
- Finite element modelling of the RRS full scale crash test.

The finite element modelling principles introduced in thesis respect the complexity of road barrier crash simulation. Proposed approach is used in selected case studies with different impact scenarios. Case studies deal with different impacts from small passenger car to HGV. Road barriers in case studies represent the real structures, typical for the European roads. All simulations in thesis were done in Pam Crash VPS Solution v.2011 and v.2020.

3/ Calibration of the virtual simulation approach using the real crash test data.
An integral part of the model validation is comprehensive database of physical crash test results. This database was completed within the thesis preparation works and is continually supplemented. Complete data package in the database has been measured by German accredited laboratory. The content of the database is unique and similar information source has never been published. A distinctive part of the test samples is completed by detailed technical report. However, the content of technical reports is confidential.

The simulation results were compared with their physical tests. Maximal 10% difference in value of the main evaluation parameters e.g., dynamic deflection or residual deformation was observed. This can be considered as a reasonably good agreement that correspond with the other published studies. It should be noted that the test results are not known in advance. This fact was principal assumption for simulation case studies in this thesis.

There are fundamental limitations of the proposed simulation method, which has been found:

- in tests with the small cars, the parameters defining the occupants load (ASI, THIV, etc.) do not correspond well with the real test results. Therefore, detailed model of the impact vehicle is crucial. In other words, the passenger load is affected by the vehicle stiffness (perhaps more than road barrier stiffness). If we do not have an appropriate vehicle FE model, it is not possible to get the same acceleration response inside the vehicle, from which ASI is calculated.
- random effects of the crash test such as tyre discharge cannot be predicted, but it is possible to investigate their consequences, if happen.

The case studies overview is shown in Tab. 25. The difference in percentage indicates how different is the simulation result from physical test result. Positive value means that the simulation gets the higher values, therefore it is conservative. Acceptance criteria "OK" signifies that simulation outputs match with the physical test. Complete verification and conformity assessment of all case studies is described in Appendix 1.

Tab. 25: Simulation case studies – results summary

Case study No.	1	2	3	4	5	6	7	8
Test Description	TB51	TB11	TB51	TB51	TB51	TB81	TB81	TB11
Impact vehicle	Bus	Small car	Bus	Bus	Bus	Truck + trailer	Truck + trailer	Small car
Impact energy [kJ]	316,2	42,1	292,8	285,5	294,8	774,4	721,2	40,6
Maximal dynamic deflection	-3.5%	+4.7%	N/A	-7,1%	+10%	7,8%	-1,6%	0%
Maximal residual deformation	+2.9%	+3.8%	N/A	-20%	+13,5%	14,9%	+13,6%	0%
Contact length	-11.8%	-27.2%	N/A	-11%	-20,8%	-13,3%	+22,7%	-18%
Vehicle cockpit deformation index	OK	OK	N/A	N/A	N/A	N/A	N/A	OK
Impact severity index ASI	N/A	+94%	N/A	N/A	N/A	N/A	N/A	+68%

4/ Specification of the theoretical model uncertainties with respect to the physical crash test.

Thanks to nonlinear dynamic simulations approach, it is possible to analyse influence of the model uncertainties on the test result. Model uncertainties concerning the road barrier testing and simulation were identified, described, and divided into four groups:

- Loading effect and structural resistance uncertainties
- Geometrical uncertainty (dimensions of main component and installation dimensions)
- Measuring uncertainty arising from the methodology of the dimension measurement
- Installation uncertainty arising from different installation methods and working practice.

The loading effect uncertainties were considered further in the sensitivity analysis.

5/ Analysis of the influence of model uncertainties on crash test results.
Load effect model uncertainties represents the basic variable related to the accuracy of physical or probabilistic model. Initial test conditions model uncertainties (mass of the vehicle M, impact velocity v, impact angle θ) were analysed in thesis and results indicates:

- the maximum total difference of dynamic deflection D between two extreme cases (still meeting the test setup requirements) is 0.14 m, which is 16.3% of the result of the crash test simulation.

- the model uncertainty (e.g., initial conditions) affect the test results in the way that classification of the road barrier working width *W* could be finally specified in different class. For example, virtual simulation including the model uncertainty predicts *W3* class results and physical test shows class *W4*.

In the case of crash tests given in standards, the model uncertainties have significantly lower importance than in the case of ordinary traffic crash. That is due to the fact that the impact conditions in crash test are mostly well defined, including their tolerances. However, results of the sensitivity analysis show that the influence of the model uncertainties on the crash test results is not negligible. Therefore, even in the case of crash test, the loading conditions cannot be considered as a deterministic value only.

6/ Proposal of the probabilistic assessment method to evaluate the safety performance of the road barrier imposed by real impact in ordinary traffic.

The probabilistic model of the road barrier impact presented in this work is based on the vehicle lane leaving and collision into the obstacle model. The probabilistic analysis is based on the assumption that the impact energy does not exceed the critical impact energy value $P(E_{\mathrm{imp}} \geq E_{\mathrm{krit}})$. In our case study the dynamic deflection of the barrier D_{dyn} is considered as characteristic parameter defining the ULS threshold. The probability of the structural failure, when the critical value of impact energy (or maximal acceptable dynamic deflection) is exceeded, is defined in thesis:

$$P(E_{\mathrm{imp}} \geq E_{\mathrm{krit}}) = n.t_{\mathrm{ref}}.\lambda.\Delta x.P(½.M.(V_{\mathrm{imp}}.\sin\theta)^2 \geq E_{\mathrm{krit}}))$$

Basic variables in limit state function above do not contain the model uncertainties. It is advisable to consider in the limit state function the model uncertainties related to the accuracy of physical or statistical model. The model uncertainties Θ_{E} for loading effects affect the value of the impact energy E_{imp} and the structural resistance Θ_R model uncertainties affect the critical energy E_{krit}. Complementary information provides this thesis in part 3.3.

Test scenario from simulation case study no.1 was chosen to illustrate the application of probabilistic methods for crash-loaded road barrier structures in ordinary traffic. Therefore, in probabilistic case study, we focus on one heavy truck impact. The impacting vehicle differs significantly from the vehicle in the crash test. However, this was the intent of this example. The procedure is given in several steps.

- Four basic variables to describe the stochastic effects were defined: mass of the vehicle *M*, impact velocity *v*, impact angle *θ* and ultimate strength of the barrier post and guardrail material f_u [MPa].
- Based on the probabilistic model of basic variables, the matrix of realisations is obtained (NLDFEA simulations), so that the whole design domain is sufficiently described. *Latin Hypercube Sampling* (LHS) method has been used to reduce the computational complexity of the crude Monte Carlo method.
- Results of simulation show that in 10% of the impacts, the barrier is overcome, which always means a non-compliant result. In the next step the main statistical coefficients of the simulation results set are determined. Additional parameters of the distribution are estimated based on visual histogram processing.
- Probability of the failure $P_f = 0{,}14$ for the given accidental impact corresponds to reliability index $\beta=1{,}1$ which could be considered to provide reasonable reliability level for the safety barrier exposed to impact of the heavy truck.

This part of the thesis also describes the differences in next applications of the probabilistic approach, particularly the evaluation of a modified road barrier structure and the assessment of a crash test.

14.2 Conclusions of the bridge pier impact force analysis

Last part of the thesis deals with application of NLDFEA simulations to estimate the real contact force from the extraordinary impact of truck into the bridge pier. This task is based on the fact, that the accidental impact forces caused by the road vehicles given in the Eurocodes are rather low, even though they do not consider additional road barrier protection of the structure. Therefore, the simulation approach is used to determine the level of the impact force into the bridge pier, which is protected by the road barrier. Further conclusions are also summarized with regards to the research questions given in introduction.

7/ Refinement of the existing analytical vehicular impact models to complete with the road barrier features.

In the thesis, the analytical modelling of event is proposed the to be divided into 5 main phases. Each phase represents individual event. Previous phase output is further used as initial conditions for next phase.

- Phase 1 – Initial conditions
- Phase 2 – Impact point. Vehicle just contact with road barrier
- Phase 3 – Road barrier overcame. Road barrier deformation capacity is exhausted.
- Phase 4 – After overcoming
- Phase 5 – Impact to obstacle

8/ Implement the numerical simulation methods to assess the impact force to the bridge pier imposed by LGV

Impact scenario with bridge structure and LGV were chosen to obtain the initial model. Two variants of initial model were further considered in the case studies:

- LGV impact into the unprotected bridge pier. This simulation is an initial model for further analysis.
- LGV impact into the bridge pier, protected by road barrier. The initial model is completed by the road barrier.

9/ Analysis of the impact force in case of unprotected bridge pier

Assessment of the simulation results are based on two main indicators, *vehicle – pier contact force* and *pier deformation*. Vehicle - pier contact force in the simulation represents the accidental design force in EN1991-1-7.

Simulation results show direct link between the vehicle stiffness (mainly the cab in that case) and contact force time history. The average value of the contact force for a soft vehicle (corresponds with the Eurocode premises) can be found around 2000kN, with peak values app. 4000 - 5000 kN. Vehicle model complexity and structural stiffness affect the maximal peak of the contact force. The reasonable extreme cases were shown in the thesis.

10/ Analysis of the impact force in case of bridge pier with road barrier protection

Although the steel road barrier cannot withstand the strongest impacts, it is beneficial to protect the bridge piers and other important structures, because:

- the road barrier absorbs at least a part of the impact energy by its deformation although it is overcome by the impacting vehicle.
- the redistribution of the initial impact conditions into the bridge pier, e.g., reducing speed, changing the angle of impact, change offset relative to the pier etc. This may in some cases lead to the fact that the vehicle misses an obstacle.

The following conclusions arise from case studies.

- Worst impact case studies results confirm that the impact forces might be x-times higher than those recommended in EN, ISO and others, in accordance with some previous published studies.
- Initial *Vehicle – Bridge pier* contact force value for LGV is around 800 -1800kN, with maximal peak values app. 2000 - 10000 kN, depending on the road barrier structure, distance from bridge pier, configuration of terrain and vehicle model complexity.
- Vehicle model complexity affects the maximal contact force peak. Simulation case study with improved vehicle model (more realistic) shows that contact forces are different and reduced app. by 50% in their peak values. However, the initial contact values remain the same.
- It is possible to update the estimation of the Vehicle – Bridge pier contact force value. The initial value is around 800 -1800kN, with peak values in range of 1800 - 5000 kN. Maximal peak values were reached 70-130ms after first vehicle – pier contact.
- Evaluation of the bridge pier loading based on the Force impulse (N.s) could be beneficial. Maximal peak of the contact force represents a simple comparable parameter. Therefore, impulse of the contact force provides more complex view on the bridge pier loading.

It is shown that the outcomes of the thesis could be generalized for safety performance evaluation of the steel road barrier products in many different impact scenarios, e.g. in a crash test, real impact in ordinary traffic or in a protection of the bridge piers.

15 Conclusions application

15.1 Application of the thesis methods and conclusions

From the scientific point of view the NLDFEA combined with probabilistic methods is convenient to be applied in the assessment and development of protection systems in case of different accidental situation. Typical example is determination of impact design forces due to an intentional impact by a truck to important objects, e.g., buildings, bridges, or safety systems. It is the recent social topics closely related to potential terrorist attack using the hostile vehicle.

From an industrial point of view the NLDFEA combined with probabilistic methods is convenient to apply for design, testing and approval of road barrier structures. However, the crash test, at present, is the only one which is recognized. The results of validated simulations may be used for ***modification*** of road barriers design approval only. More details referring to the road barrier modification approval procedure can be found in [28].

15.2Thesis work perspectives

The road barrier crash analysis and bridge pier impact force imposed by LGV is wide topic and this thesis is dealing with it only partly. In the view of continuing of this work there are a few topics, that are suitable for further investigation and analysis, including

- Specification of requirements for the target reliability level of road barriers in accidental design situations. It would be appropriate to open a dialogue about the target reliability index value for road barriers and similar structures in the road vicinity.
- Proposal of methodology for the probabilistic and risk engineering methods with support of NLDFEA to assess the consequences of road barrier structural failure in accidental situation (considering the barrier overcome or collision with HGV or LGV).
- HGV and LGV model improvement in order to get a more realistic impact force response in later phase of the bridge pier impact (secondary peak).
- Application of the thesis approaches on concrete road barriers. In particular the thesis and its outcomes deal with the steel road barrier with posts rammed into the soil or clamped into the bridge parapet only.
- Proposal for the suitable substitution of the bridge pier contact force time history by its simplified course. This could be beneficial in case of the analytical calculation (dynamic force approach).

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Kalinský M., Cohí P.: Non-destructive lateral crash simulation on the sled – concept ALIS, European safety conference Crash Tech 2018, Ingolstadt

Jelínek J., Růžička M., Kalinský M.: Advanced Methods in Crash Safety Testing, 56th International conference EAN 2018, Technical University of Liberec.

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Marková J., Kalinský M., Marek P.: Alternative procedures for the assessment of road safety barriers. European safety and reliability conference Esrel 2013, ISBN 9781138001237, Taylor & Francis Group, 2014, pp. 2515-2520.

List of the research and commercial projects

TACR Grant project TA 02030150: Application of reliability methods in research and verification of innovative road safety barriers, 2012 – 2014.

TACR Grant project TE01020020: Josef Bozek Competence Centre for Automotive Industry – work package WP23. Use of simulation methods for modern vehicle body design in the perspective of reducing weight and increasing passive safety, 2012-2017.

Application of nonlinear dynamic analyses in testing and certification of truck cab strength according to Regulation ECE R29.03, Methodology accredited by Czech Institute of Accreditation 05/2012.

Grant project CG711-040-160, Czech Ministry of Transportation: Passive safety of children in cars (2007-2011, MD0/CG).

Grant project 1F54G/106/150, Czech Ministry of Transportation: Study on improving the safety of passengers in buses with primary focus on simulating a rollover (2005-2009, MD0/1F).

Commercial project: Development of the unique test rig and methodology for non-destructive lateral crash simulation on the sled and catapult– concept ALIS, 2017-2020.

Commercial project: Road barrier crash tests simulation according to EN 1317-2 for European and Czech manufactures, 2012 – 2018.

Commercial project: Certification of vehicles via computer simulations for Hyundai Motor Company, R & D Centre Jeonju Korea, Certification of the trucks (strength cab) and buses (rollover) based on the results of FEA, 2012 – 2014.

Commercial project: Certification of buses according Regulation ECE R66.02 (rollover) using computational simulation for Solaris Bus & Coach SA, Poland, 2007 – 2014.

Used software

Simulations: Pam Crash VPS Solution v.2011, v.2020

Model preparation: Visual Enviroment, Ansa v.19.1.0

Results evaluation: Visual Enviroment, Meta v.19.1.0, MS Excel**,** National Instruments DIAdem

In Prague, 16.11.2021 Ing. Michal Kalinský

CZECH TECHNICAL UNIVERSITY IN PRAGUE

KLOKNER INSTITUTE

RELIABILITY ASSESSMENT OF ROAD RESTRAINT SYSTEMS

Appendix 1: Case studies simulation results and verification

Doctoral thesis

Ing. Michal Kalinský

Prague, November 2021

Table of content:

A1.1 Appendix 1: Case studies simulation results and verification

Appendix 2 present the results of the road barrier crash test case studies presented in thesis. Total of 8 case studies were chosen to verify the numerical simulation approach, see Tab.A1. Results of case study no 1 and 2 are already shown in thesis. Rest of the case studies no. 3 - 8 are presented in Appendix 1. Complete list of the simulations is shown in Tab.A1. Case studies conclusions are summarized in the last section.

Tab.A1: Verification case studies overview

Case study no.:	Test identification	Post anchorage	Road barrier design	Information source	Note
1	TB 51	Ground	Steel, Post C, Guard rail 2x A	Test Report	see thesis
2	TB 11	Ground	Steel, Post C, Guard rail B	Test Report	see thesis
3	TB 51	Ground	Steel, Post C, Guard rail A	Test Report	test failed
4	TB 51	Ground	Steel, Post C, Guard rail 2x B	Test Report	see App.1
5	TB 51	Bridge parapet	Steel, Post C, Guard rail B	Test Report	see App.1
6	TB 81	Bridge parapet	Steel, Post C, Guard rail B	No	see App.1
7	TB 81	Bridge parapet	Steel, Post C, Guard rail B	Test Report	see App.1
8	TB 11	Ground	Steel, Post C, Guard rail 2xB	Test Report	see App.1

Procedure of the case study results verification is divided into four phases, as is shown below:

- Phase 1: Case study description. General information about the test scenario, impact vehicle and road barrier test sample.
- Phase 2: General information about the crash test. This part provides the general information about the real full-scale physical crash, e.g. the impact conditions and if the technical report with more details is available or not.
- Phase 3: Simulation model provides all relevant information about the FE models used in simulation, e.g., the impact vehicle, road barrier, anchorage simplification etc.
- Phase 4: Case study verification is described in comparison table, where all parameters are shown both for the physical crash and simulation. Comparison parameters are split into four main groups:
  - Impact vehicle
  - Impact conditions
  - Road barrier properties
  - Test results

Verification is further completed with comparison of the test results in computer simulation and real crash test using the graph of the post deformation, top view picture of the vehicle movement (if available in real) and residual deformation of the road barrier. The simulation output is supplemented by additional information e.g., the contact force time history and energy balance of the calculation.

A1.2 Case study no.3

Numerical simulation of the simulation case study no.3 represents the physical test TB 51 with failed results. This test has been conducted with bus and road barrier made of steel installed (rammed) into the soil. Road barrier test sample is typical product used along central Europe incl. Czech Republic. Road barrier structure is like test sample in case study no.1, with extended pitch of the posts up to 1,3m. This design change significantly affected the structural resistance of whole system. This case study is aimed to check the simulation trustworthy if the failure of the system could be expected based on the virtual results only.

A1.2.1 Crash test general information

Bus hits the road barrier with the actual impact speed 71,42 km/h and actual angle 20 deg. Initial conditions are within the tolerance defined in EN1317.

Actual impact speed and actual angle combination is also within the tolerance envelope defined in EN 1317. During and after the impact no more than one wheel of the vehicle passes over the rearmost part of the deformed system. Vehicle does not roll over during the test and no more than 5% of the cargo has been separated in the vehicle till the stop.

Information package related to the road barrier and crash test has been completed by Technical Report from the physical test. Information contain in the report has been utilized to validate the simulation approach in detail.

A1.2.2 Simulation model global information

With regards to the real tests the bus hits the road barrier 0,4m left from the post no.20. The initial conditions such an impact velocity, vehicle test mass and impact angle fully correspond with the real crash test values. Therefore, the impact energy is also the same.

It is obvious from the Technical Report that real test was failed, due to the vehicle overcome and main longitudinal part crack. In the simulation was considered the initial phase of the crash only. This phase is up to first 500ms after first contact. The evaluation of further crash behaviour (more than 500ms) is highly affected by random features and therefore may have no sense.

Simulation model consist of the following main parts:

- Impact vehicle:
    - Fully deformed vehicle with the kinematic suspension and rotating wheels.
    - Modified frontal part – to match with the testing vehicle. Frontal part of the vehicle has significant effect to the test result.
    - Defined pressure inside the tyres.

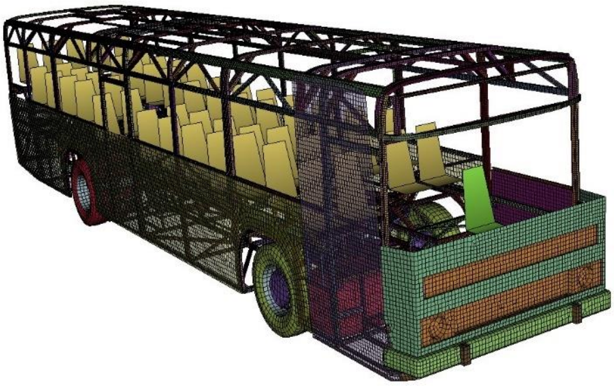

Fig. A1: Impact vehicle FE model in simulation case study no.3

- Road barrier model features:
  - Total length of 88m.
  - Bolts model – in crash zone only.
  - Total of 68 posts fixed 270 mm under the road.

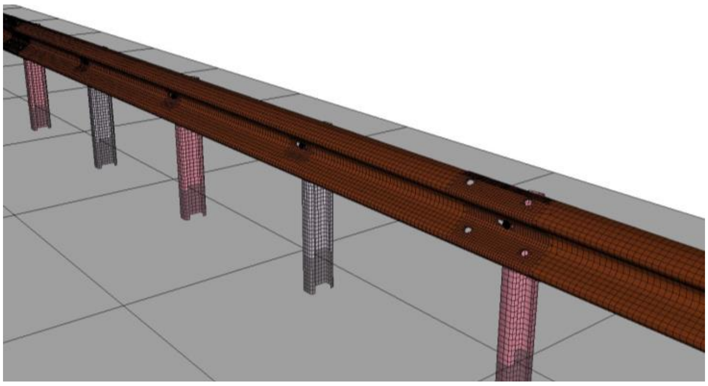

Fig.A2: Road barrier FE model in simulation case study no.3

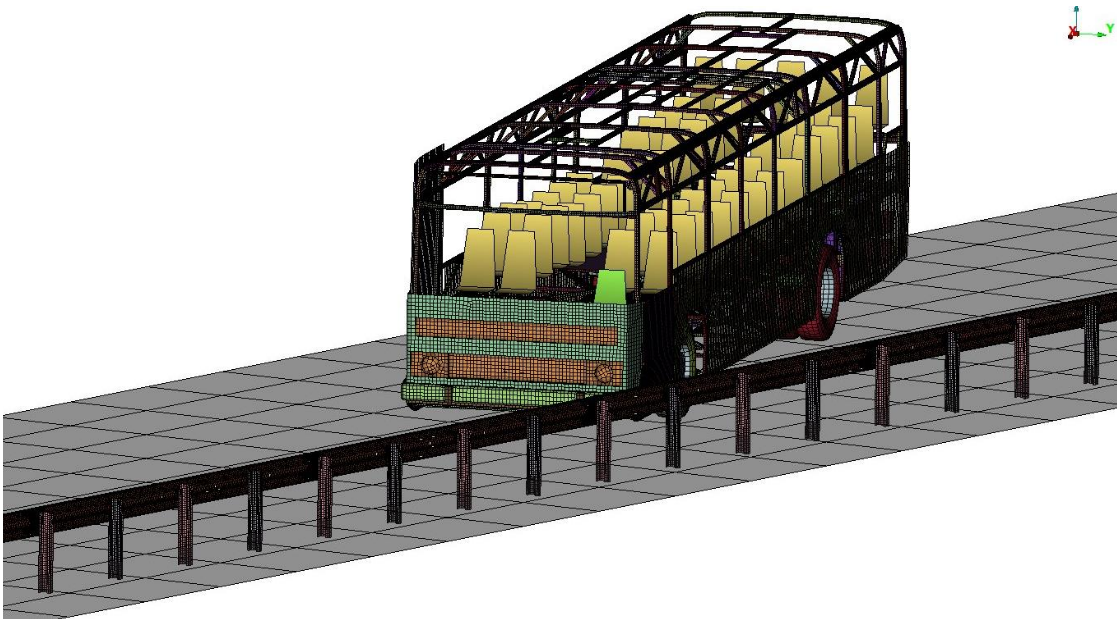

Fig.A3: Overall view of the numerical model from simulation case study no.3

A1.2.3 Case study no.3 verification

Verification of the case study no.3 is not complex, compare to other cases due to the non-compliant result. Therefore, no exact parameters were evaluated. Vehicle – road barrier interaction indicates same behaviour in main aspects, e.g.:

- simulation shows that vehicle has tendency to overcome the road barrier. This behaviour corresponds with the real test results.
- road barrier is fully deformed and some of the posts have contact with ground.

For verification of the numerical model in case study no.3. is sufficient that vehicle behaviour indicates same trends to overcome the barrier and barrier shows similar deformation.

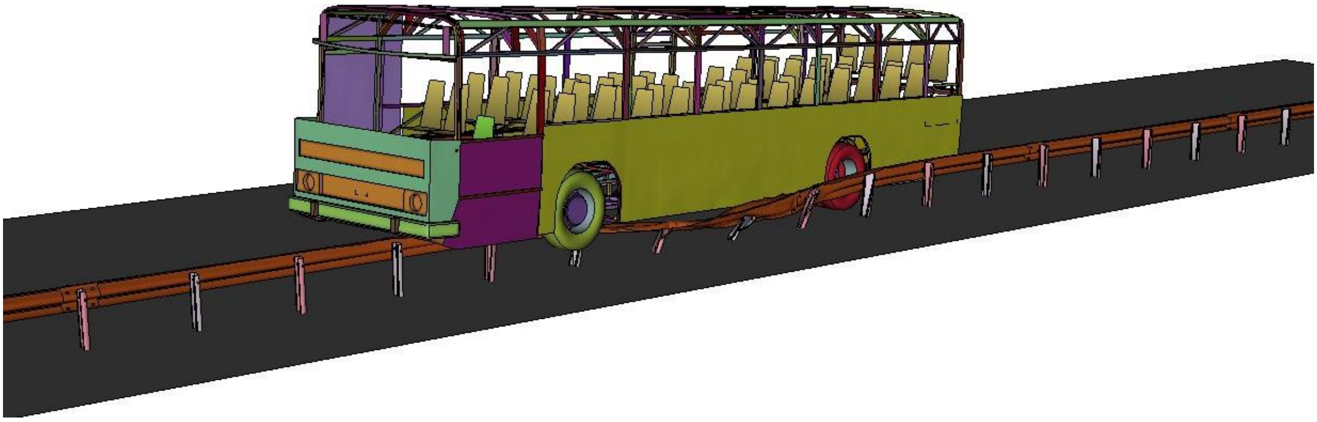

Fig.A4: Test results – simulation final state in 500ms

Tab. A2: Case study no.3- Physical test / Simulation comparison

	Parameter	Physical Test	SIMULATION No.3	Difference
Initial conditions: Impact vehicle				
	Test Type acc. To EN 1317	**TB 51**	**TB51**	
	Vehicle type and model	Karosa C700, 1991	Karosa C700	
	Vehicle kerb mass [kg]	9294	N/A	N/A
	Total test mass [kg]	12660	12660	0%
	Dimension – length [mm]	11055	11880	+7,4%
	Dimension – width [mm]	2500	2500	0%
	Dimension – height [mm]	N/A	3275	N/A
	Wheel base [mm]	5600	5950	-2,4%
	Wheel track – front [mm]	1955	2050	-2,4%
	Wheel track – rear [mm]	1810	2000	+11%
	Nb. of axles	1S+1	1S+1	--
	Tyre Radius [mm]	510	518	-1,3%
Impact conditions:				
	Actual impact speed [km/h]	71,42	71,42	0%
	Actual impact speed [m/s]	19,84	19,84	0%
	Actual impact angle [deg]	20,0	20,05	0%
	Impact Energy [J]	292834	292834	0%
	Actual impact point location	0,4m left from post 25	0,4m left from post 20	
	Test track condition	Wet	Frict = 0,4	--
Road barrier properties:				
	Material -overall	Steel	Steel	--
	Ground anchor	Ground	Posts fix in -210mm	--
	Ground anchor depth [mm]	900	210	--
	System width [mm]	232	230	-0,8%
	Post spacing [mm]	1334	1334	0%
	Post cross section	C150x75x25 tl.3,5	C150x75x25 tl.3,5	0%
	Post material (indication)	S420MC	S420MC	--
	Post Yield strength Re [Mpa]	420	420	0%

	Post Ultimate strength Rm [Mpa]	480	550	+14,5%
	Post material Ductility A [%]	16	16	0%
	Guardrail thickness [mm]	2,5	2,5	0%
	Guardrail material (indication)	S420MC	S420MC	--
	Guardrail Yield strength Re [Mpa]	420	420	0%
	Guardrail Ultimate str. Rm [MPa]	480	480	0%
	Guardrail material - ductility A [%]	16	19	+19%
	Top Guardrail height - centre [mm]	730	830	0%
	Low Guardrail height - centre [mm]	575	510	0%
Test Results:				
	Test Results	NOK	NOK	--
	Dynamic deflection [m]	N/A	N/A	--
	Working width / class [m]	N/A	N/A	--
	Working width class	N/A	N/A	--
	Permanent deflection [m]	N/A	N/A	--
	Contact length [m]	N/A	N/A	--

Comparison of the post deformation (Test –Simulation) graph and other parameters, particularly *Dynamic deflection D, Vehicle intrusion VI, Working width W* and *Contact length between the vehicle and road barrier* are not relevant due to the test failure.

The simulation and real crash test vehicle movement is compared in Figures A5 and A6. Simulation finish after fist 500ms, while real crash test continues. This is shown in pictures no 1-3 in the real crash top view in Fig.A6.

Vehicle in real test was automatically braked after app. 2 sec. after contact. To simulate this last phase of the crash event is not important. Therefore, no vehicle movement trajectory was evaluated.

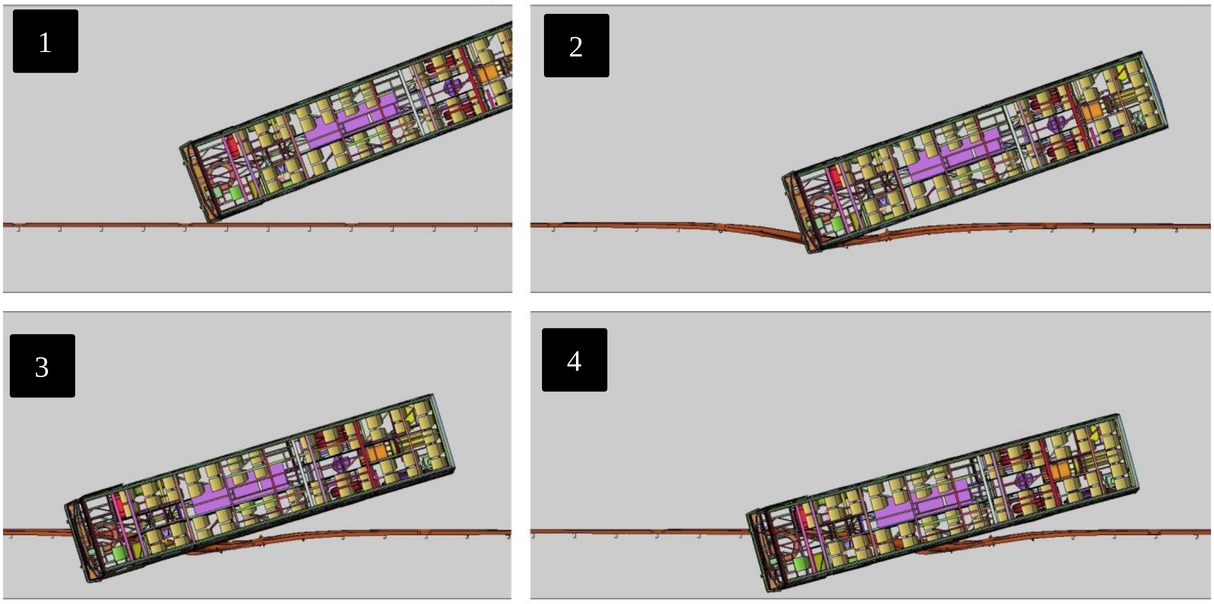

Fig.A5: Case study no.3, top view of the results- simulation

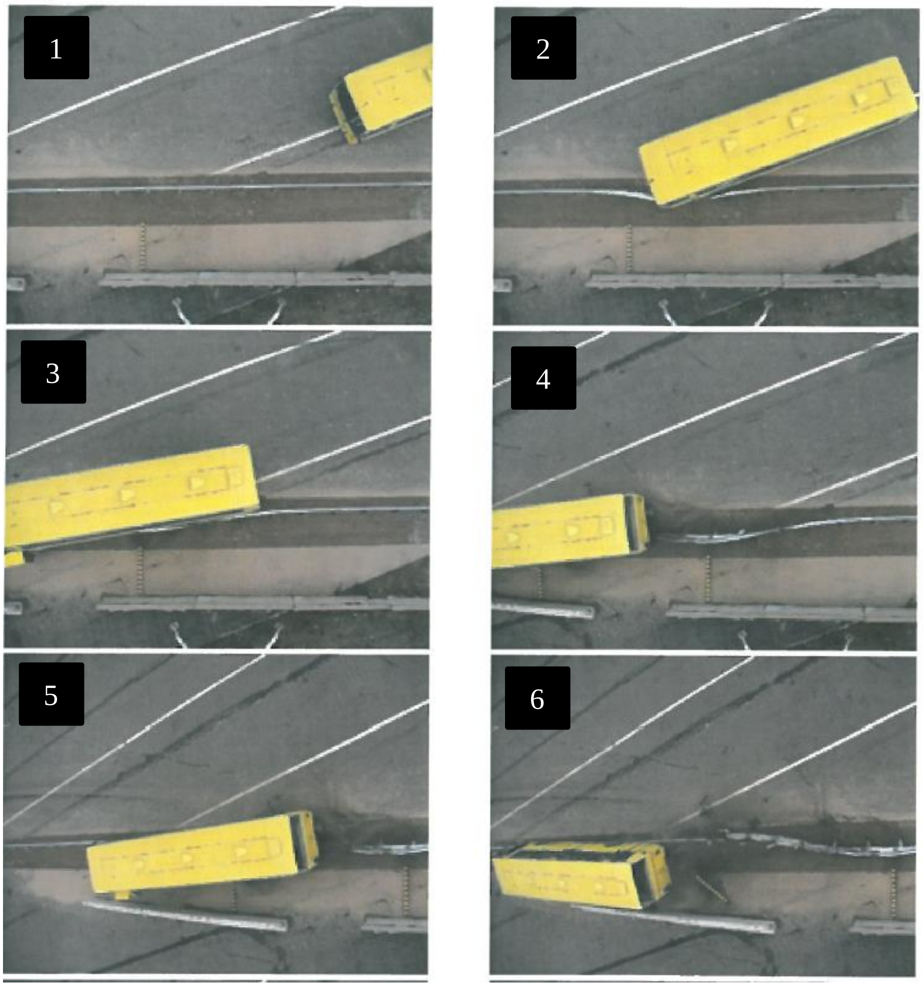

Fig. A6: Case study no.3, top view of the results – crash test

A1.3 Case study no.4

Numerical simulation of the simulation case study no.4 represents next physical test TB 51. This test has been conducted with bus- coach type and road barrier made of steel installed into the soil. Tested road barrier sample has double side 3vawe B profile guardrail with post distance of 750mm. Road barrier system is the same product as used in case study no.8 for test TB11.

A1.3.1 Crash test general information

Bus hits the road barrier with the actual impact speed 70,5 km/h and actual angle 20,0 deg. Initial conditions are within the tolerance defined in EN1317. Actual impact speed and actual angle combination is also within the tolerance envelope defined in EN 1317. During and after the impact no more than one wheel of the vehicle passes over the rearmost part of the deformed system. Vehicle does not roll over during the test and no more than 5% of the cargo has been separated in the vehicle till the stop. Information package related to the road barrier and crash test has been completed by Technical Report from the physical test. Information contain in the report has been utilized to validate the simulation approach.

A1.3.2 Simulation model global information

With regards to the real test the bus impacts to the road barrier 29,9 m left from the post no.1. The initial conditions such an impact velocity, vehicle test mass and impact angle fully correspond with the real crash test values. Therefore, the impact energy 285,5kJ is also the same.

Simulation model consist of the following main parts:

- Impact vehicle:
  - Fully deformed vehicle with the kinematic suspension and revolving wheels.
  - Defined pressure inside the tyres.
- Road barrier model:
  - Total length of 82 m.
  - Bolts detailed model – in crash area only.
  - Total of 96 posts fixed just in the road level.

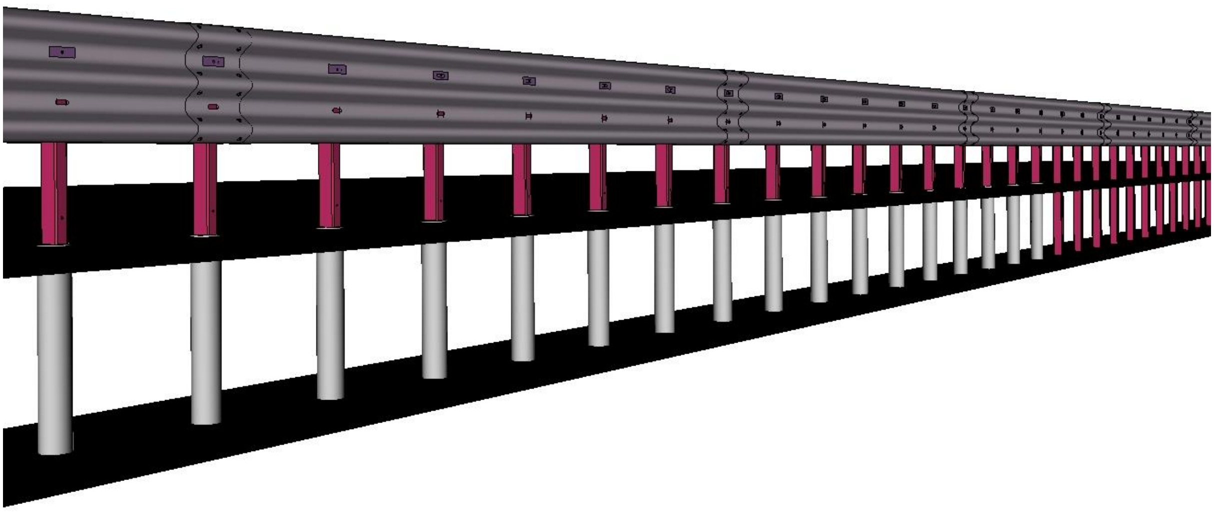

Fig. A7: Road barrier FE model in simulation case study no.4

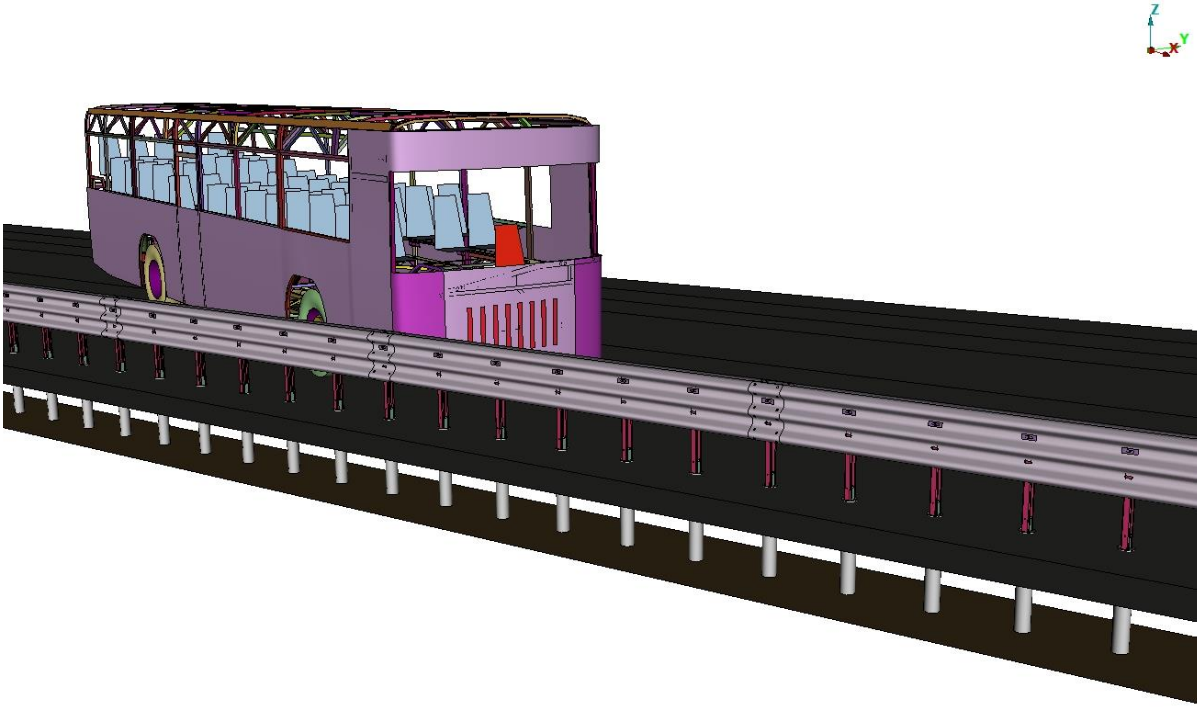

Fig. A8: Overall view of the numerical model from simulation case study no.4

A1.3.3 Case study no.4 verification

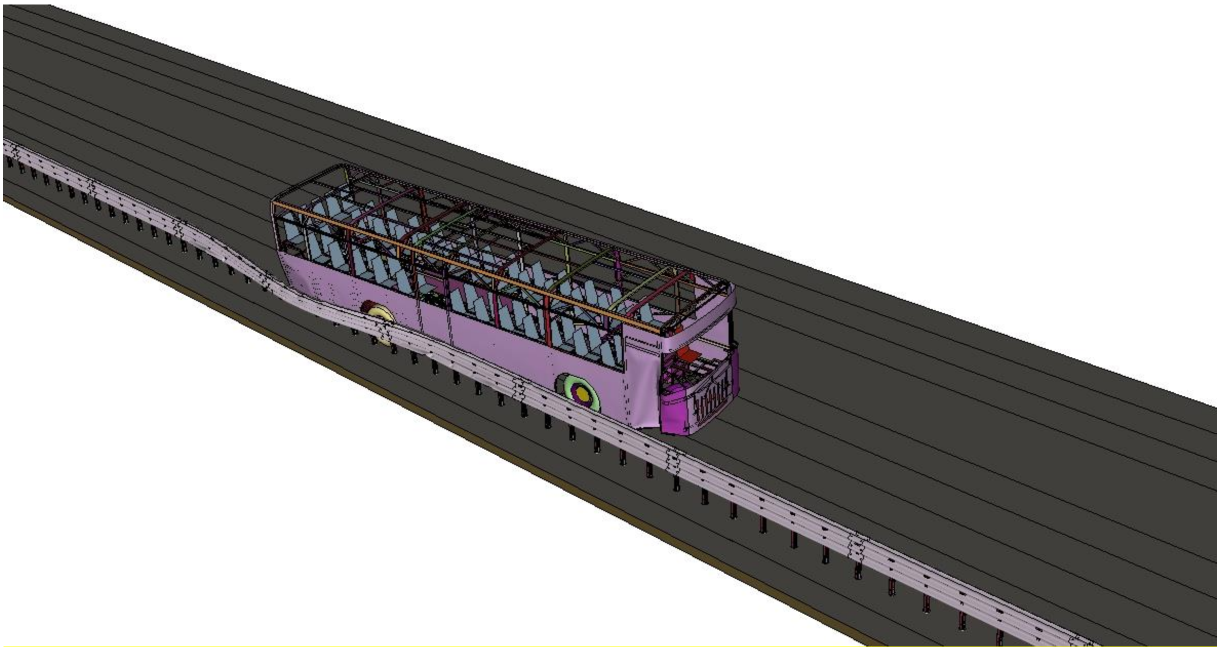

Fig. A9: Test results – maximal deflection in 700ms

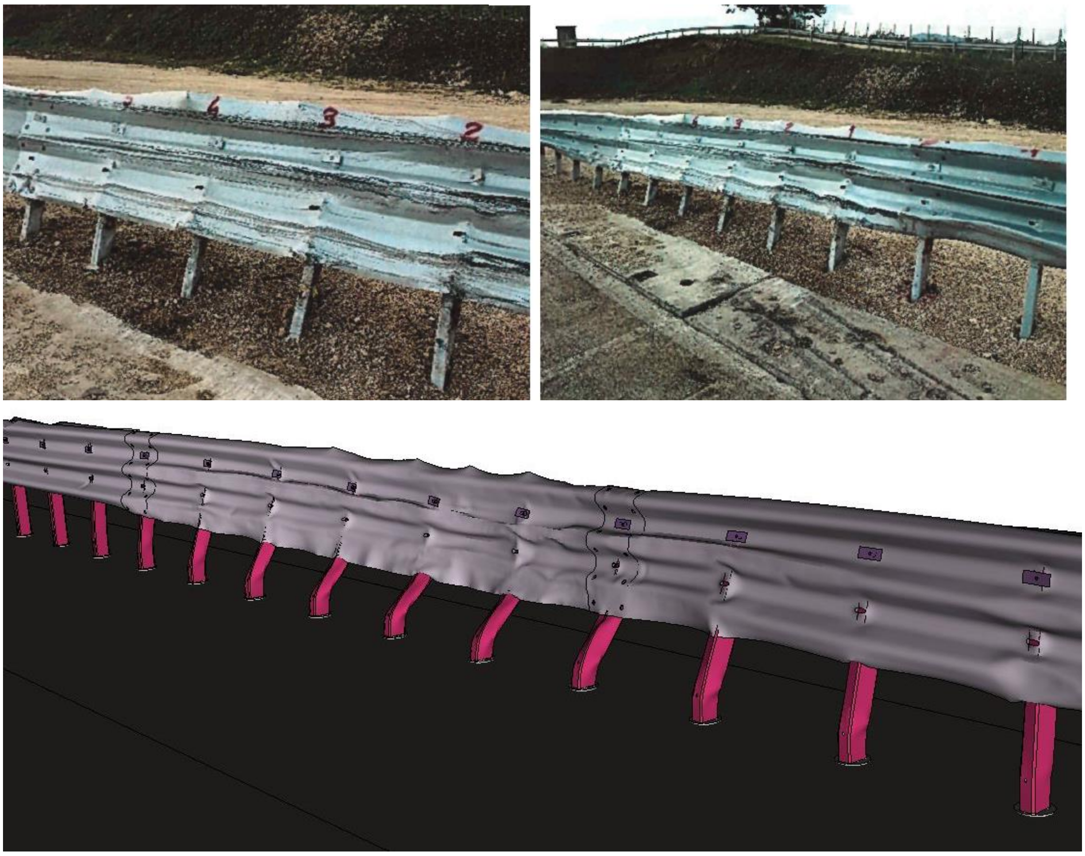

Fig. A10: Case study no.4, road barrier permanent deflection – real test/ simulation comparison

The evidence of the simulation validity is displayed on the output graphs Fig.A11-A12. Energy balance of entire calculation is shown in Fig. A11. It is obvious that calculation progress has no uncertain points or phenomena. Yellow curve represents the non- physical energy (hourglass energy) and do not exceeds the recommended threshold of 4% of total energy. Smooth energy transformation among kinetic energy (red curve) and internal energy of the system (green curve) as expected is shown in Fig.A12.

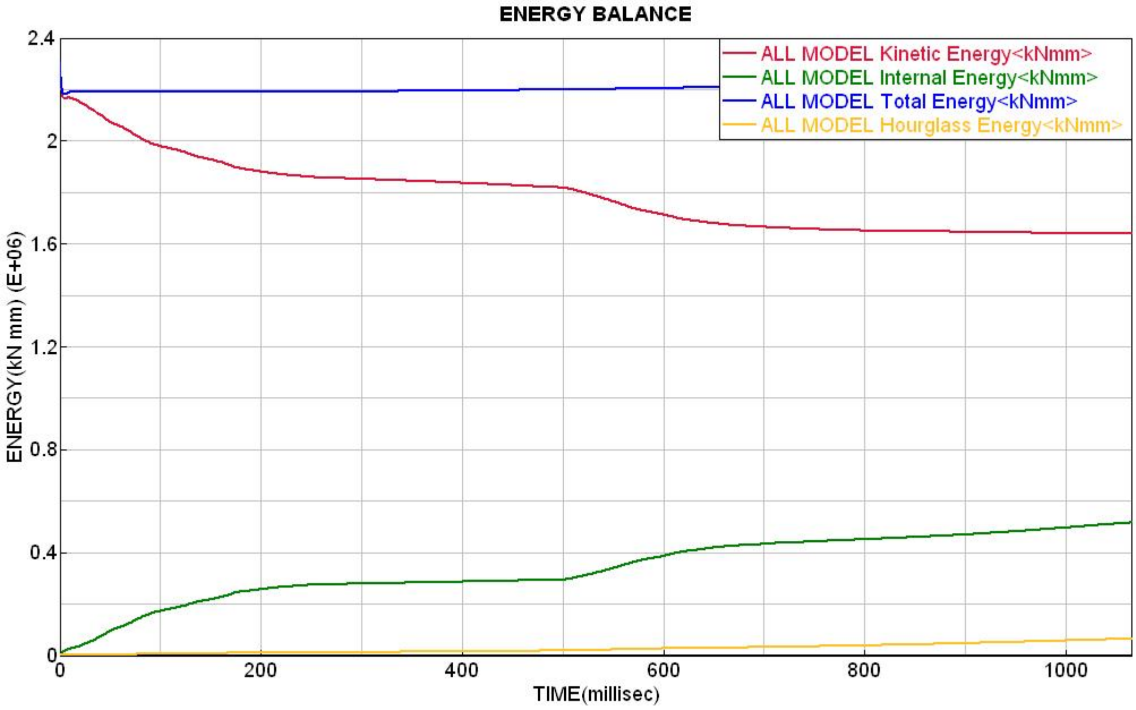

Fig. A11: Case study no.4, energy balance of the simulation

In Fig. A12 the contact force between the impact vehicle and road barrier system is shown. Graph is output from numerical simulation. This value cannot be compared with the real test due to the difficult measuring.

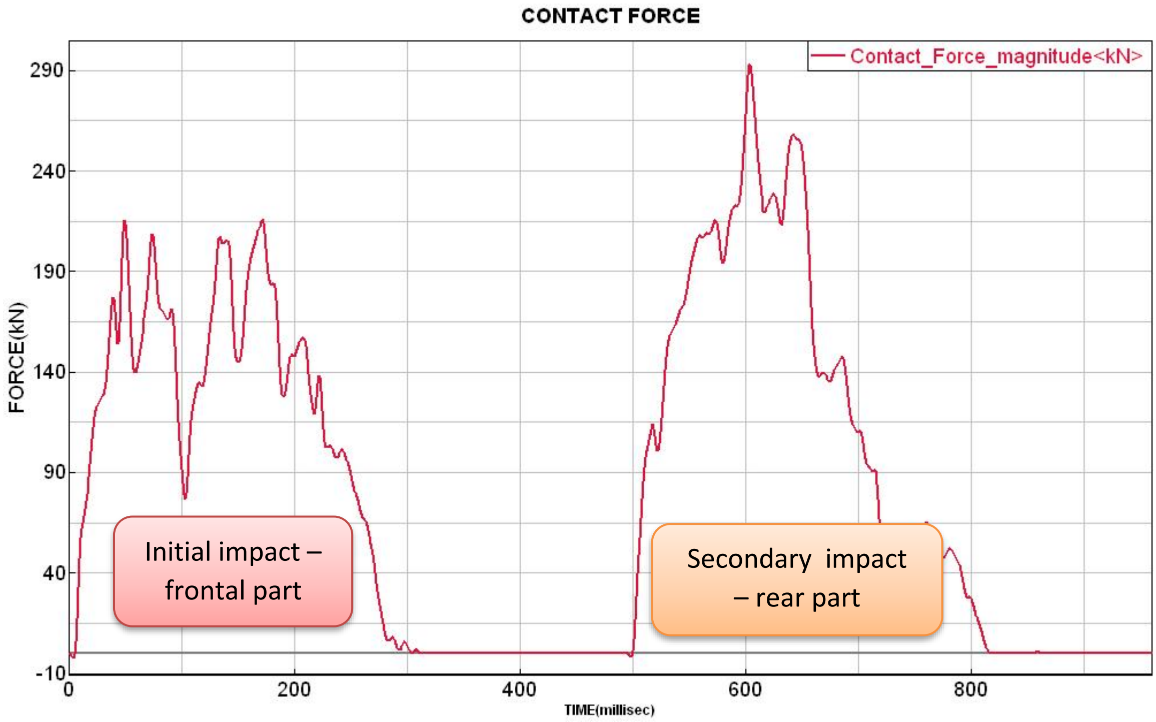

Fig. A12: Case study no.4, vehicle – road barrier contact force

Tab A3: Case study no.4- Physical test / Simulation comparison

	Parameter	Physical Test	SIMULATION No.4	Difference
Initial conditions: Impact vehicle				
	Test Type acc. To EN 1317	**TB 51**	**TB51**	
	Vehicle type and model	IVECO 370, 1988	Bus model Standard model detail see case study no.1	
	Vehicle kerb mass [kg]	12308	N/A	N/A
	Total test mass [kg]	12728	12728	0%
Impact conditions:				
	Actual impact speed [km/h]	70,5	70,5	0%
	Actual impact speed [m/s]	19,58	19,58	0%
	Actual impact angle [deg]	20,0	20,0	0%
	Impact Energy [J]	285500	285500	0%
	Actual impact point location	29,9m	0,1m left from post 25	--
	Test track condition	Dry	Frict = 0,4	--
Road barrier properties:				
	Material -overall	Steel	Steel	--
	Ground anchor	Ground	Posts fix in road	--
	Ground anchor depth [mm]	805	880	+9,3%
	System width [mm]	270	270	0%
	Post spacing [mm]	750	750	0%
	Post cross section	C100x60x25	C100x60x25	--
	Post material (indication)	S355JR	S355JR	--
	Post Yield strength Re [Mpa]	409	408	0%
	Post Ultimate strength Rm [Mpa]	506	506	0%
	Post material Ductility A [%]	24	24	0%
	Guardrail thickness [mm]	2,3	2,3	0%
	Guardrail material (indication)	S355JR	S355JR	---
	Guardrail Yield strength Re [Mpa]	471	471	0%
	Guardrail Ultimate str. Rm [MPa]	551	551	0%
	Guardrail material - ductility A [%]	23	23	0%
	Top Guardrail height - centre [mm]	647,5	650	0%
Test Results:				
	Test Results	OK	OK	--
	Dynamic deflection [m]	0,7	0,65	-7,1%
	Working width [m]	0,8	0,7	+12,5%
	Working width class	W2	W2	--
	Permanent deflection [m]	0,6	0,48	-20%
	Contact length [m]	8,2	7,3	-11%

The simulation and real crash test vehicle movement is compared in Figures A13 and A14. Simulation has been stopped after fist 1200ms, while real crash test continues.

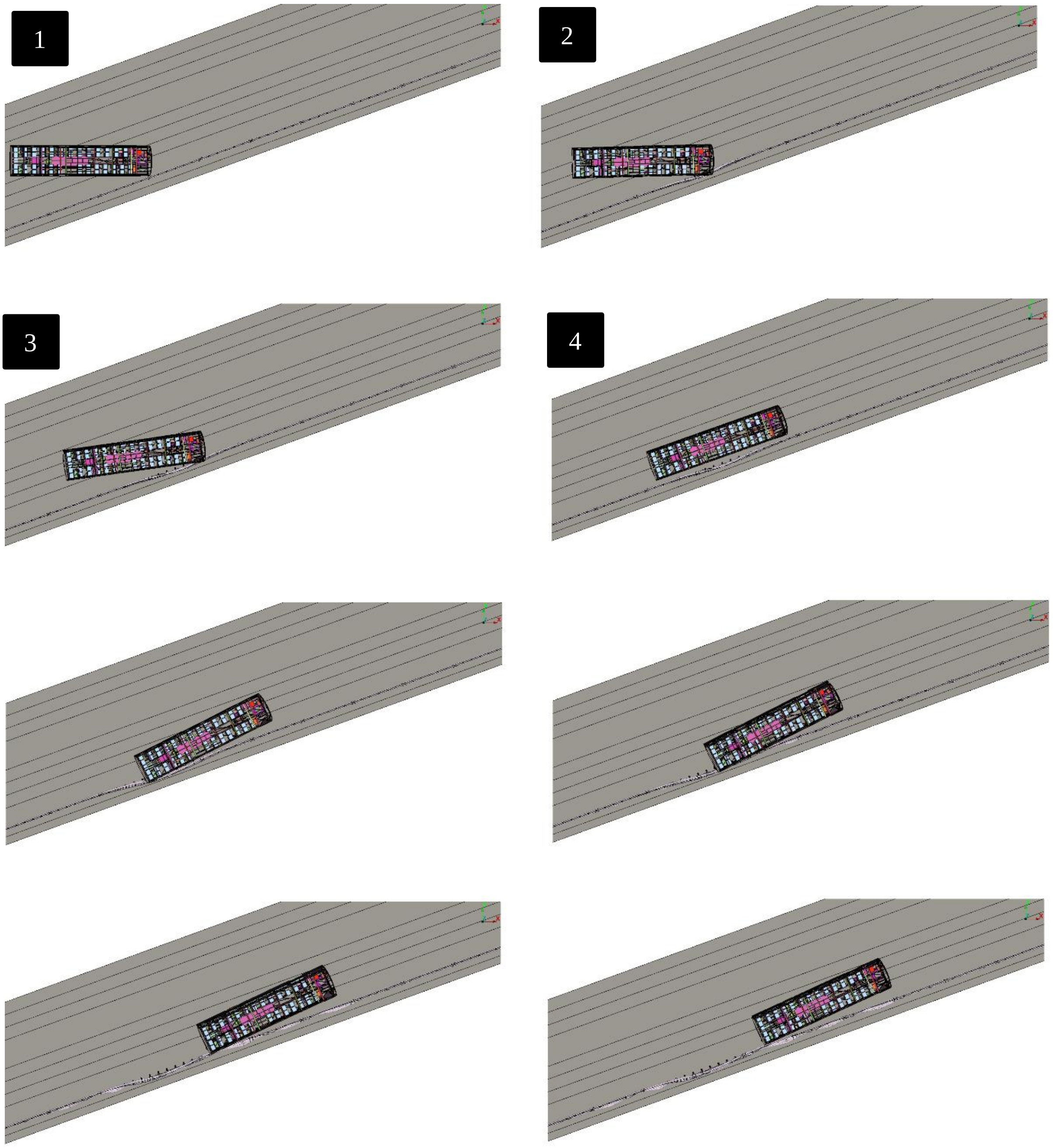

Fig.A13: Case study no.4, top view of the results - simulation

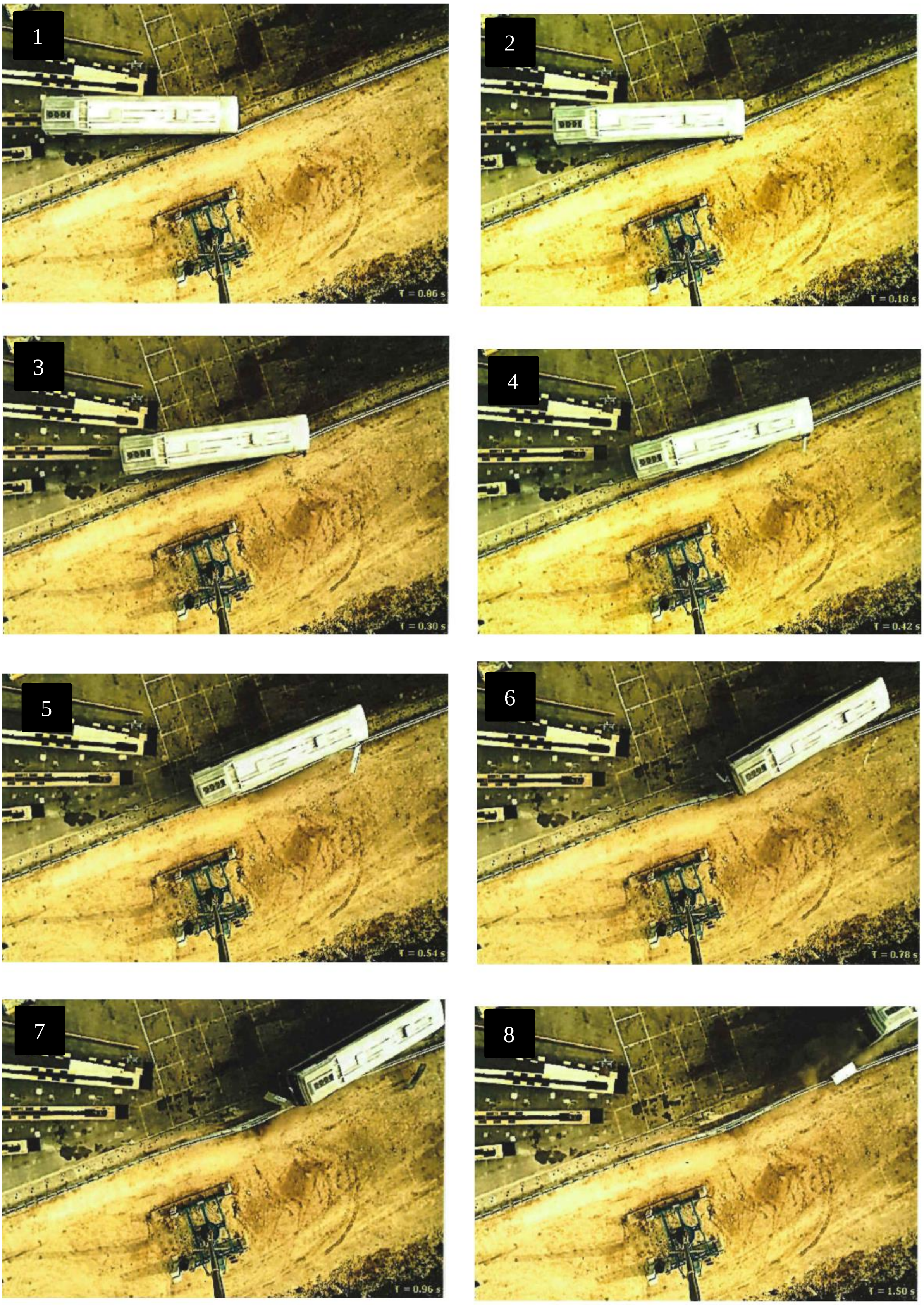

Fig. A14: Case study no.4, top view of the results- crash test

Road barrier posts residual deformation after the crash and last state of the simulation is compared in graph in Fig. A15. Two points of deformation were evaluated. The main profile point (in guardrail centre line) is shown by dot lines and low post profile point is full line.

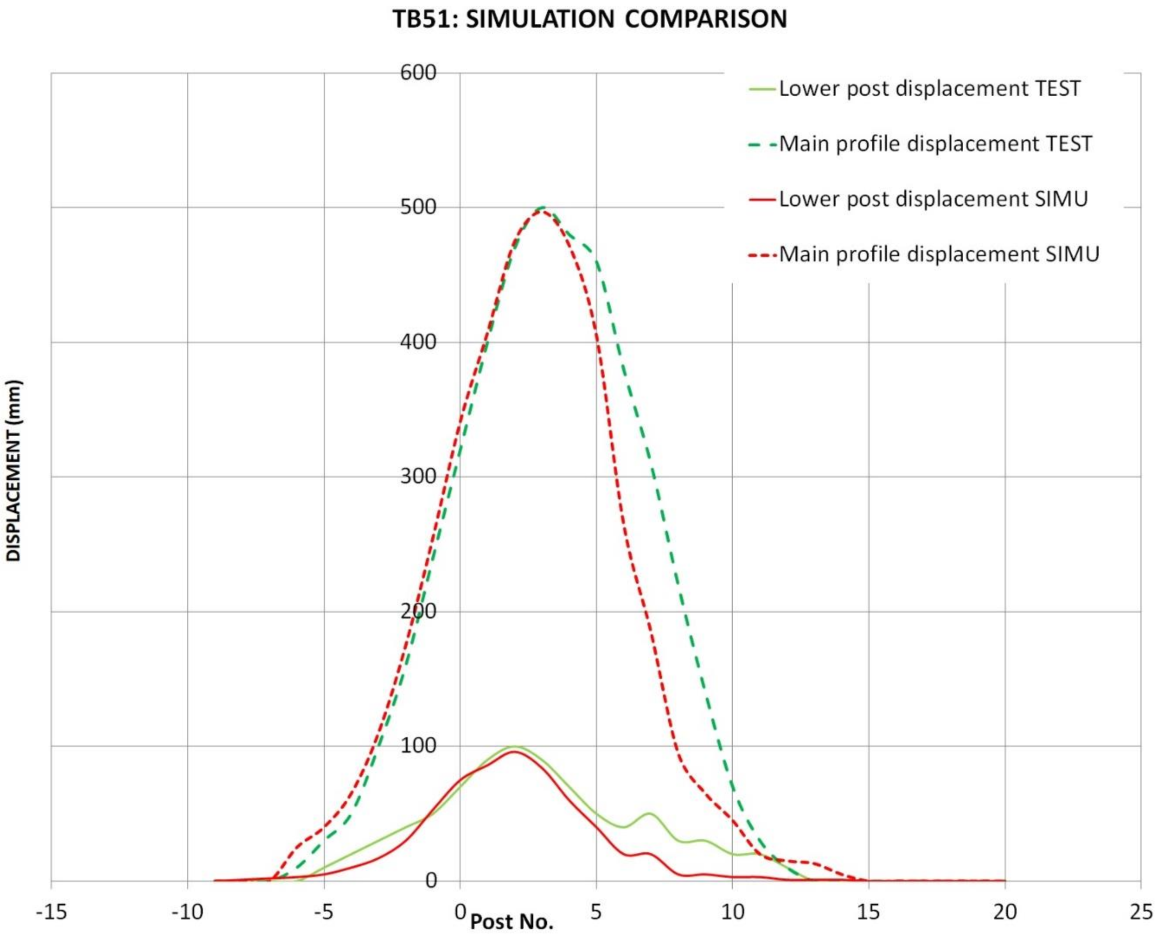

Fig. A15: Comparison of the post deformation (Test –Simulation)

A1.4 Case study no.5

Numerical simulation in case study no.5 represents the real crash test TB 51. This test has been conducted with bus- city type and road barrier made of steel installed (clamped via 4 bolts) on concrete bridge parapet height 100mm. Road barrier test sample has B profile guardrail with post distance of 3000mm.

A1.4.1 Crash test general information

Bus hits the road barrier with the actual impact speed 71,5 km/h and actual angle 20,0 deg. Initial conditions are within the tolerance defined in EN1317. Actual impact speed and actual angle combination is also within the tolerance envelope defined in EN 1317. During and after the impact no more than one wheel of the vehicle passes over the rearmost part of the deformed system. Vehicle does not roll over during the test and no more than 5% of the cargo has been separated in the vehicle till the stop.

Crash test information has been completed by Technical Report from the physical test. Information from the report has been utilized to validate the simulation approach.

A1.4.2 Simulation model global information

With regards to the real crash tests the bus impact to the road barrier 0,5 m left from the post no 5. The initial conditions such an impact velocity, vehicle test mass and impact angle fully correspond with the real crash test values. Therefore, the impact energy 294,86kJ is also the same.

Simulation model consist of the following main parts:

- Simulation model of the impact vehicle has been taken from case study no.1. The vehicle mass and impact velocity were modified acc. to the real values.
- Road barrier model:
    - Total length of 44 m.
    - Bolts detailed model – in crash area only.
    - Total of 15 posts.

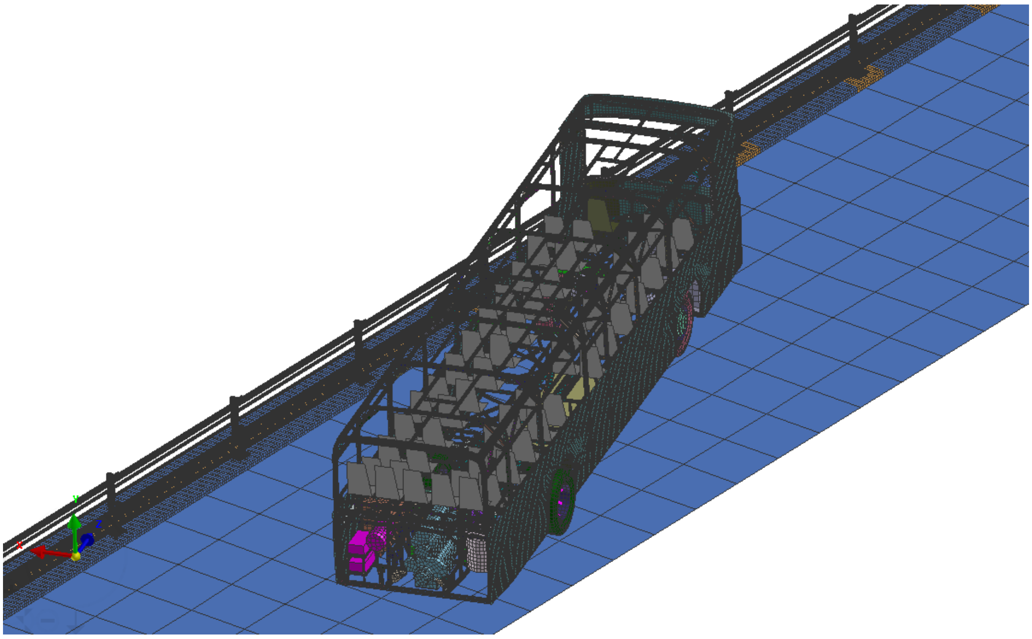

Fig.A16: Overall view of the numerical model from simulation case study no.5

A1.4.3 Case study no.5 verification

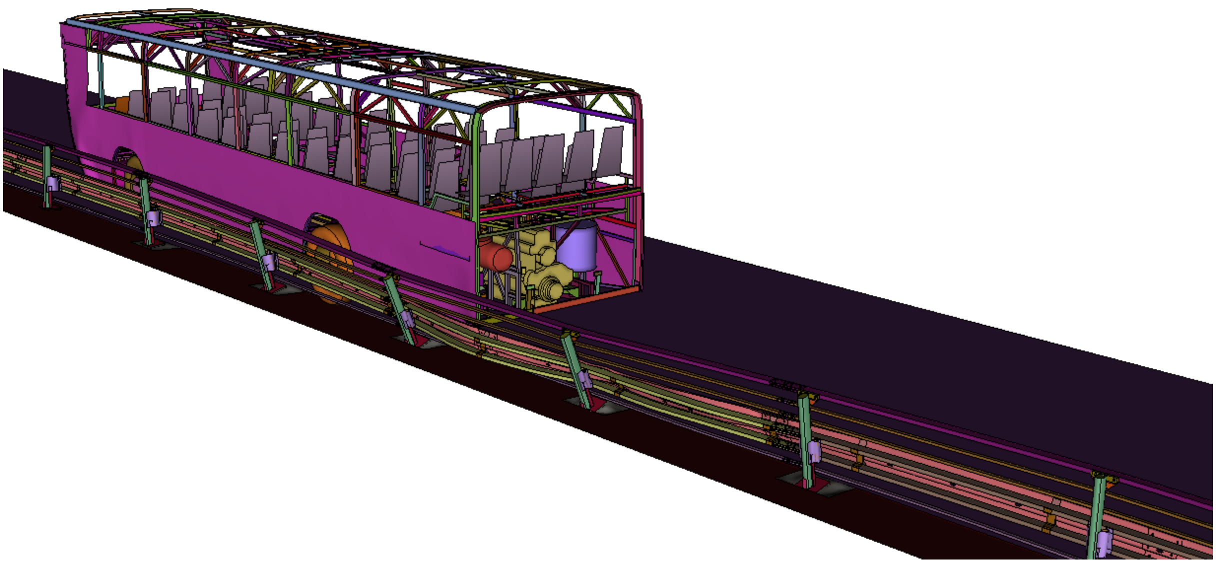

Fig.A17: Case study no.5, final state results in 900ms

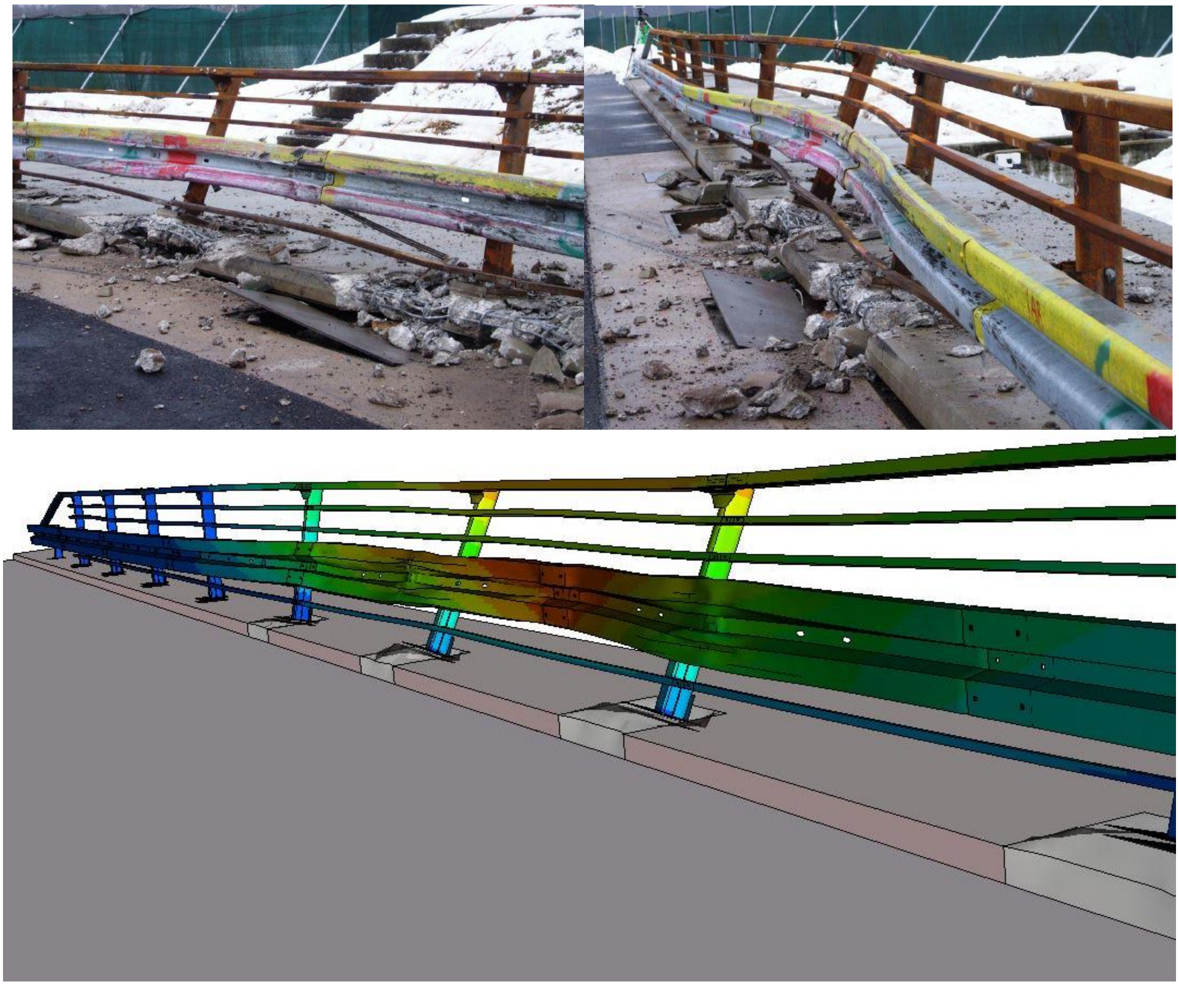

Fig. A18: Case study no 5, road barrier permanent deflection – real test/ simulation comparison

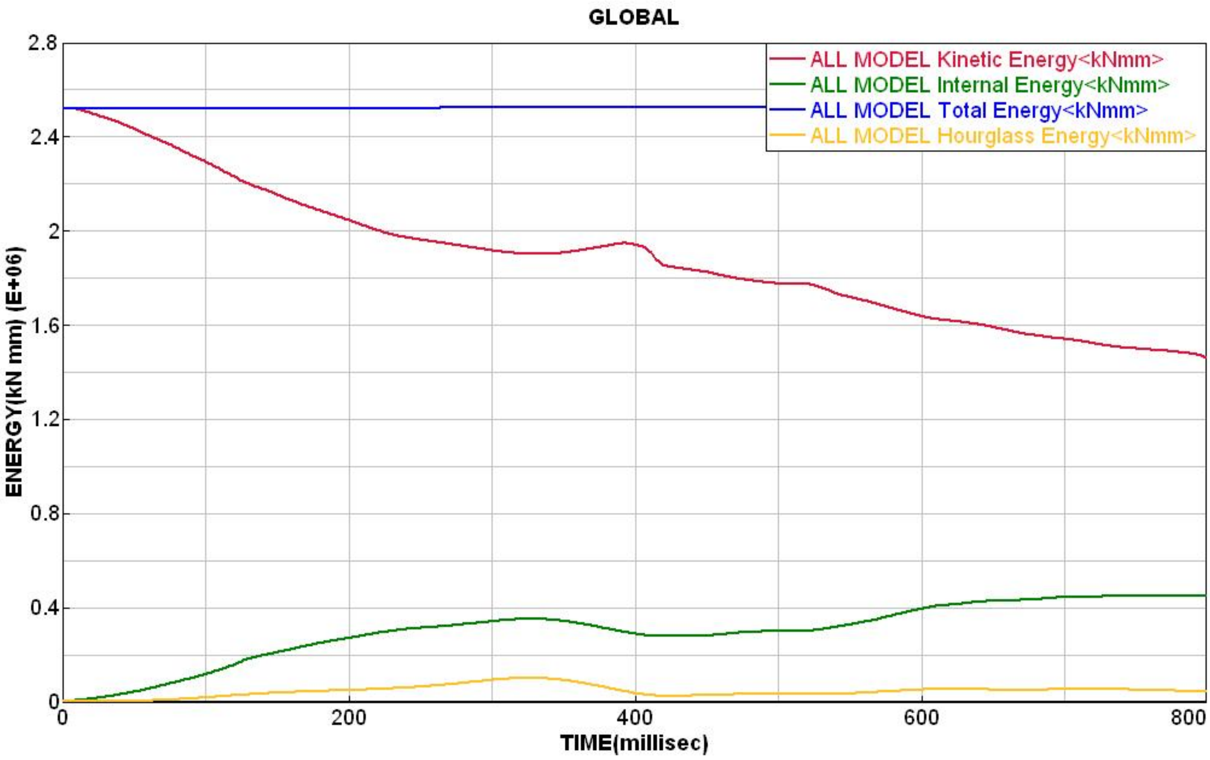

Fig. A19: Case study no.5, energy balance of the simulation

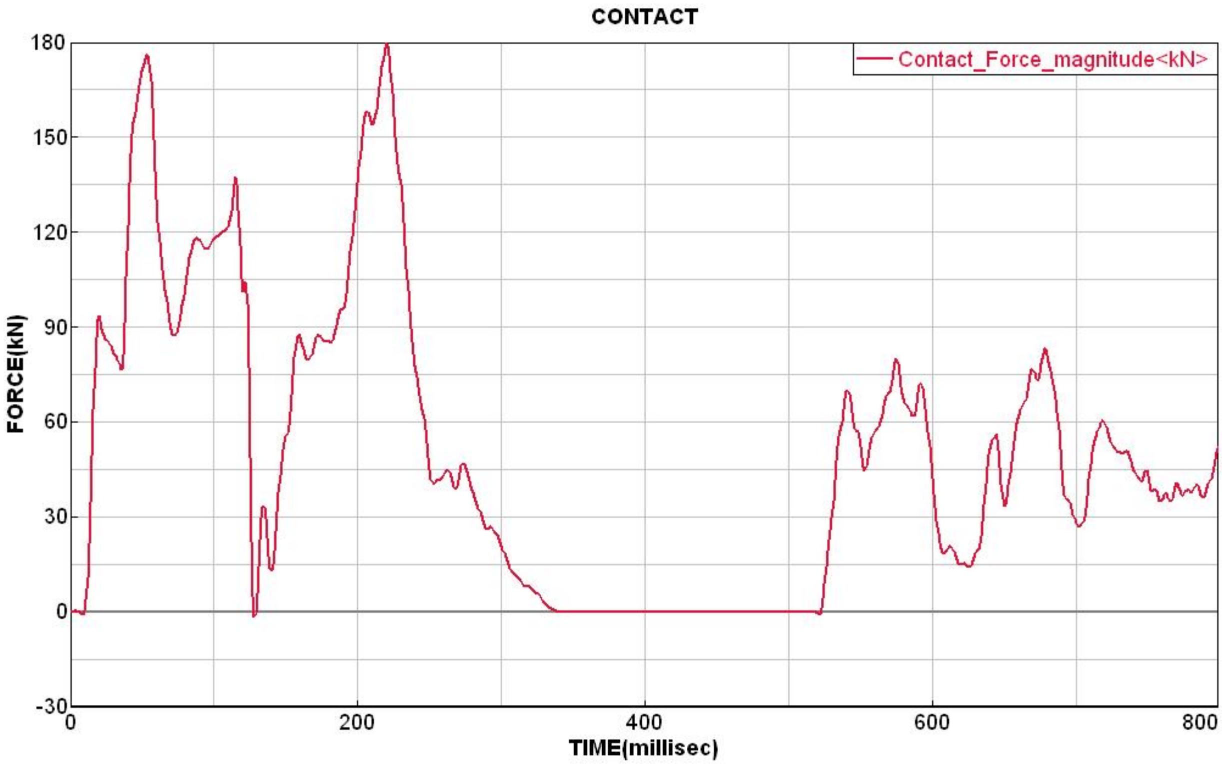

Fig. A20: Simulation No.5: Vehicle – Road barrier contact force

Tab A4: Case study no.5- Physical test / Simulation comparison

	Parameter	Physical Test	SIMULATION No.5	Difference
Initial conditions: Impact vehicle				
	Test Type acc. To EN 1317	**TB 51**	**TB51**	
	Vehicle type and model	MB 0405N, 1996	Karosa C700	
	Vehicle kerb mass [kg]	10870	N/A	N/A
	Total test mass [kg]	12780	12780	0%
	Dimension – length [mm]	11910	11820	-1%
	Dimension – width [mm]	2500	2500	0
	Dimension – height [mm]	N/A	3275	N/A
	Wheel base [mm]	5880	5950	+1,1%
	Wheel track – front [mm]	2110	2050	-2,8%
	Wheel track – rear [mm]		2000	N/A
	Nb. of axles	1S+1	1S+1	N/A
	Tyre Radius [mm]	450	518	+15%
Impact conditions:				
	Actual impact speed [km/h]	71,5	71,5	0%
	Actual impact speed [m/s]	19,86	19,86	0%
	Actual impact angle [deg]	20,0	20,05	0%
	Impact Energy [J]	294856	294856	0%
	Actual impact point location	0,48m left from post 3	0,5m right from post 5	--
	Test track condition	Wet	Frict = 0,4	--
Road barrier properties:				
	Material -overall	Steel	Steel	--

	Ground anchor	Bridge parapet	Posts fix in parapet	--
	Ground anchor depth [mm]	100	0	--
	System width [mm]	440	440	0%
	Post spacing [mm]	1500	1500	0%
	Post cross section	120x80x10+ Full profile in anchorage	120x80x10	0%
	Post material (indication)	S355J2	S355J2H	--
	Post Yield strength Re [Mpa]	N/A	443	0%
	Post Ultimate strength Rm [Mpa]	N/A		--
	Post material Ductility A [%]	N/A	27	0%
	Guardrail thickness [mm]	3,0	3,0	0%
	Guardrail material (indication)	S235JR	S235JR	--
	Guardrail Yield strength Re [Mpa]	N/A	281	--
	Guardrail Ultimate str. Rm [MPa]	N/A		--
	Guardrail material - ductility A [%]	N/A	26	--
	Top Guardrail height - centre [mm]	430 + parapet	430	0%
	Low Guardrail height - centre [mm]			
Test Results:				
	Test Results	OK	OK	--
	Dynamic deflection [m]	0,5	0,55	+10%
	Working width / class [m]	1,0	1,0	0%
	Working width class	W3	W3	--
	Permanent deflection [m]	0,37	0,42	+13,5%
	Contact length [m]	7,83	6,2	-20.8%

The simulation and real crash test vehicle movement is compared on Figures A21 and A22. Simulation has been stopped after fist 800ms, while real crash test continues.

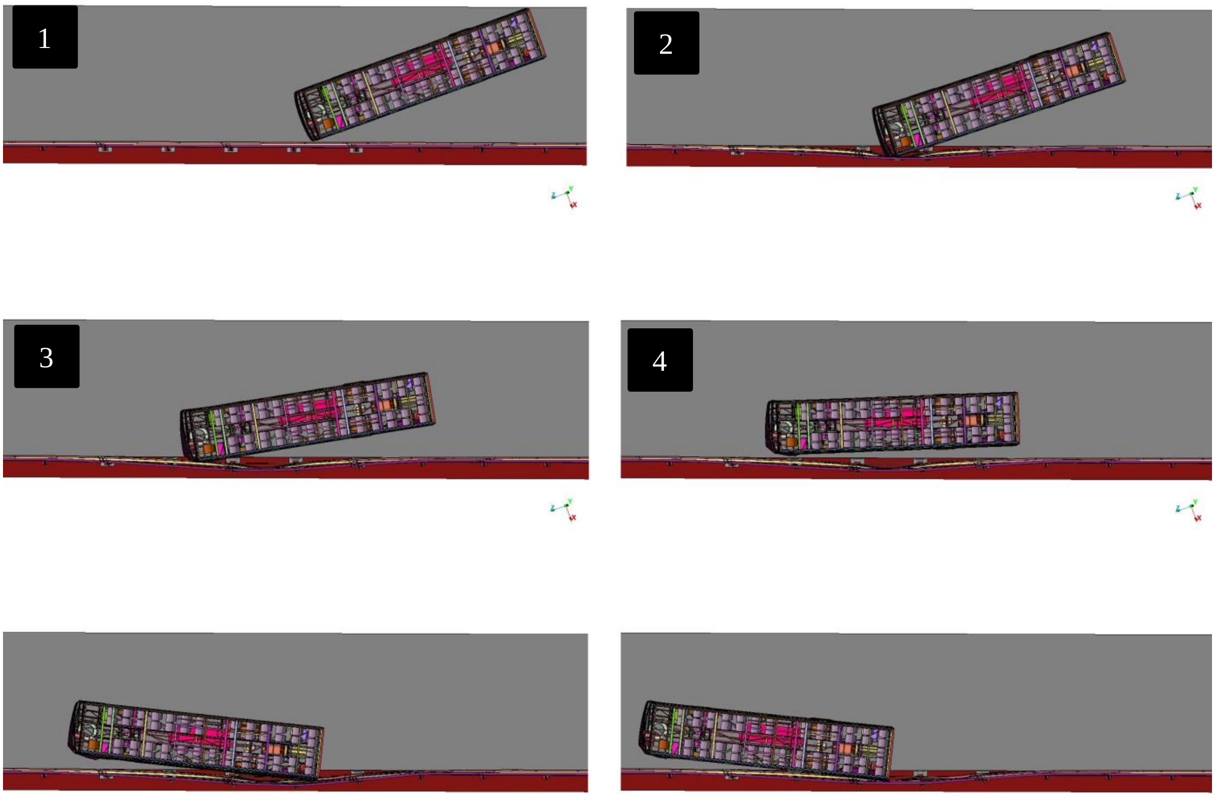

Fig.A21: Case study no.5, top view of the results - simulation

Simulation results were calculated up to 800ms after first contact with the road barrier. This is shown in pictures no. 1-5 on the real crash top view in Fig.A22.

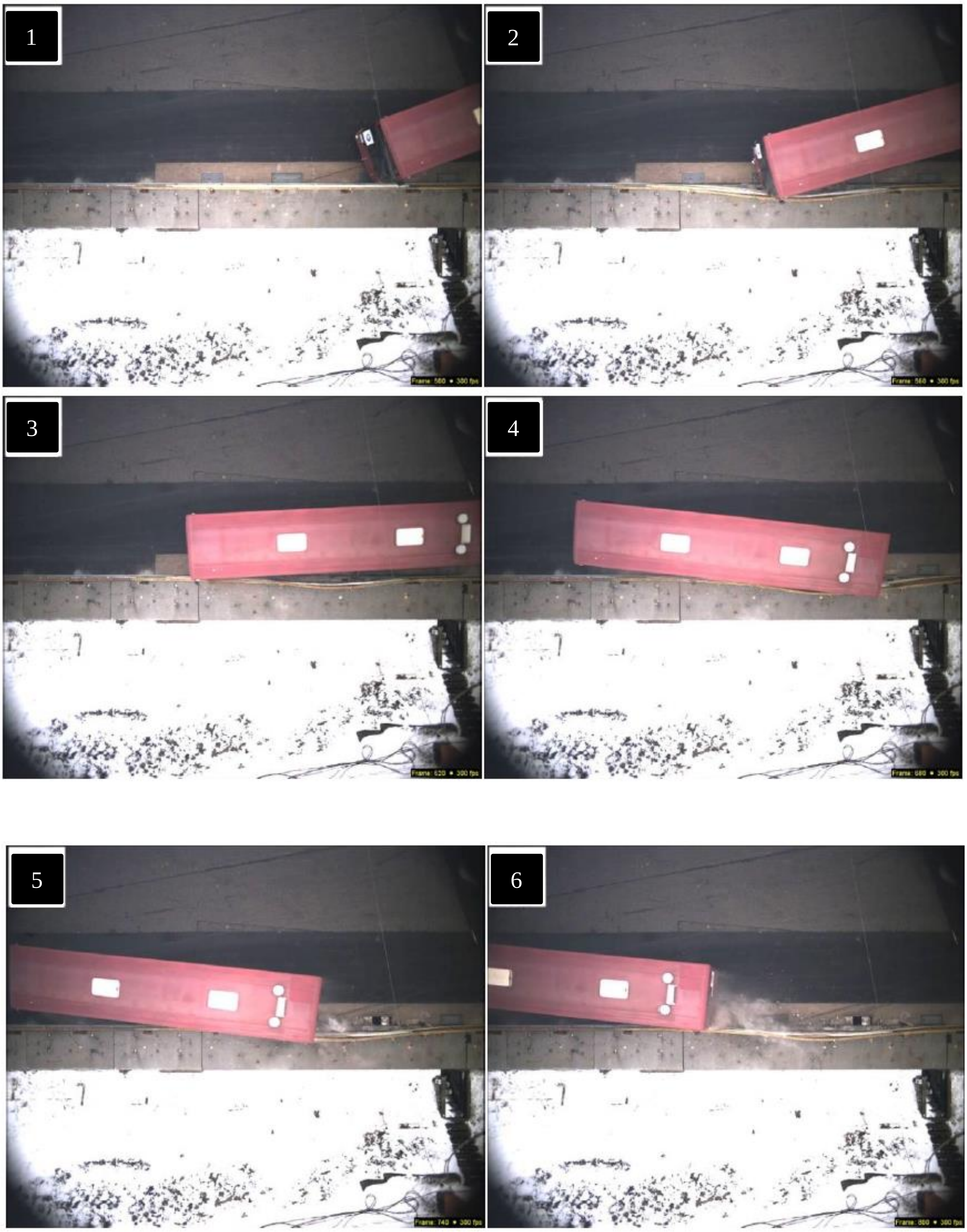

Fig.A22: Case study no.5, top view of the results – crash test

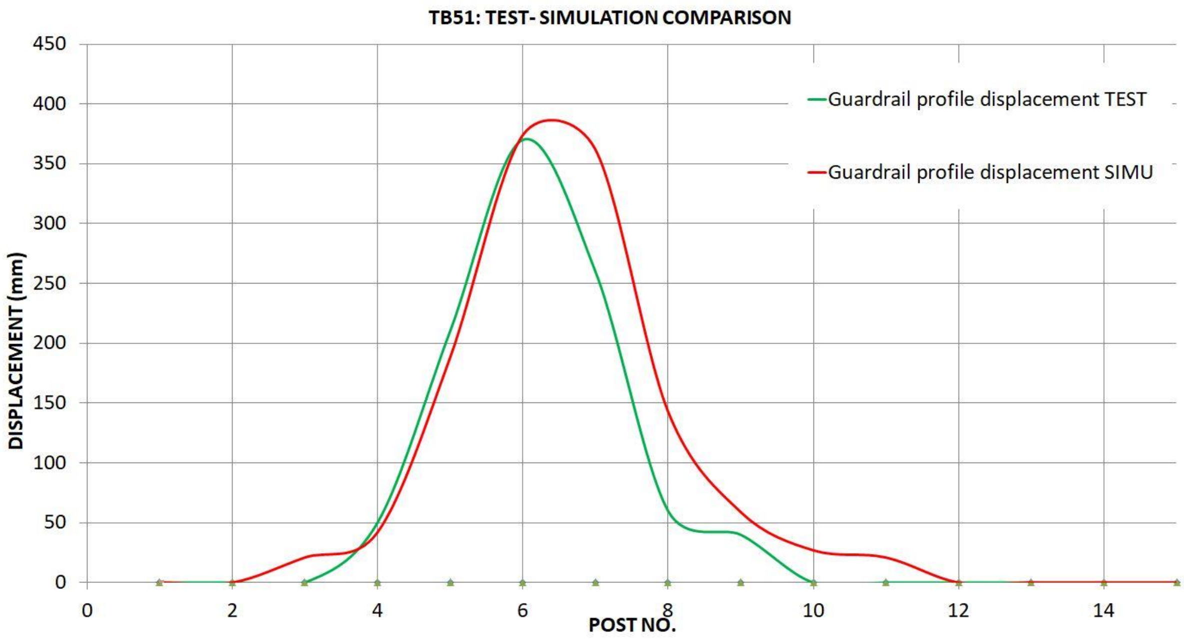

Fig. A23: Comparison of the post deformation (Test –Simulation)

A1.5 Case study no.6

Numerical simulation of the simulation case study no.6 represents the real crash test TB 81 with road barrier clamped into the bridge parapet. This test has been conducted with truck and trailer. Road barrier is made of steel installed on the bridge parapet – see Fig. A24. The height of the parapet is 70mm from the road level and made of B25 concrete. Unfortunately, no technical report was available to get more information about crash test details.

A1.5.1 Crash test general information

Truck with mass 38340kg impact the road barrier with the actual impact speed 66,9 km/h and actual angle 20 deg. Initial conditions are within the tolerance defined in EN1317. Actual impact speed and actual angle combination is also within the tolerance envelope defined in EN 1317.

The posts are placed on the anchors, which are embedded in the foundation, and connected using 4 screws. The guardrail beams are connected to each second posts by collapsible elements. The guardrail beams are the B profile. The handrail is screwed on the top sides of the posts. Road barrier frontal face offset from the parapet is 500mm (behind the parapet). The system length in test is 79,5m incl. leading and trailing terminal section.

During the impact the following vehicle damage has been observed:

- Steering broken
- Flat tyres on axle 1 and 2
- Underrun protection, air tank and side panel detached from vehicle

During and after the impact no more than one wheel of the vehicle passes over the rearmost part of the deformed system. Vehicle does not roll over during the test and no more than 5% of the cargo has been separated in the vehicle till the stop.

Road barrier damage after the impact has been observed. Post 26 (mass 38kg) was detached and finished 0,85m in perpendicular to the road direction behind the barrier and 4,5m along the traffic direction.

A1.5.2 Simulation model global information

With regards to the real tests the truck impacts the road barrier 0,4m before transition element no.5 and 6. The initial conditions given by impact velocity, vehicle test mass and impact angle fully correspond with the real crash test values. Therefore, the impact energy 774,4 kJ is also the same. The simulation model was completed by the deformable material in post anchorage zone.

Simulation model consist of the following main parts:

- Impact vehicle:
    - Fully deformed truck and trailer with the kinematic suspension and revolving wheels. Trailer is connected to the truck via kinematic joint.
    - Defined pressure inside the tyres.
- Road
    - Rigid body definition.
    - Bridge parapet 160mm.
    - Deformable area in post anchorage location – representing the concrete deformation capacity.
- Road barrier model:
    - Total length of 60 m.
    - Bolts detailed model – in crash area only.
    - Total of 41 posts fixed on the bridge parapet with crushable zone under the post foot.

A1.5.3 Case study no.6 verification

Overall view on the simulation results in 1000ms after first contact is shown in Fig.A24. Impact vehicle has tendency to overcome the road barrier. however, test finished successfully. The vehicle behaviour under impact cannot be assessed due to the missing information to compare.

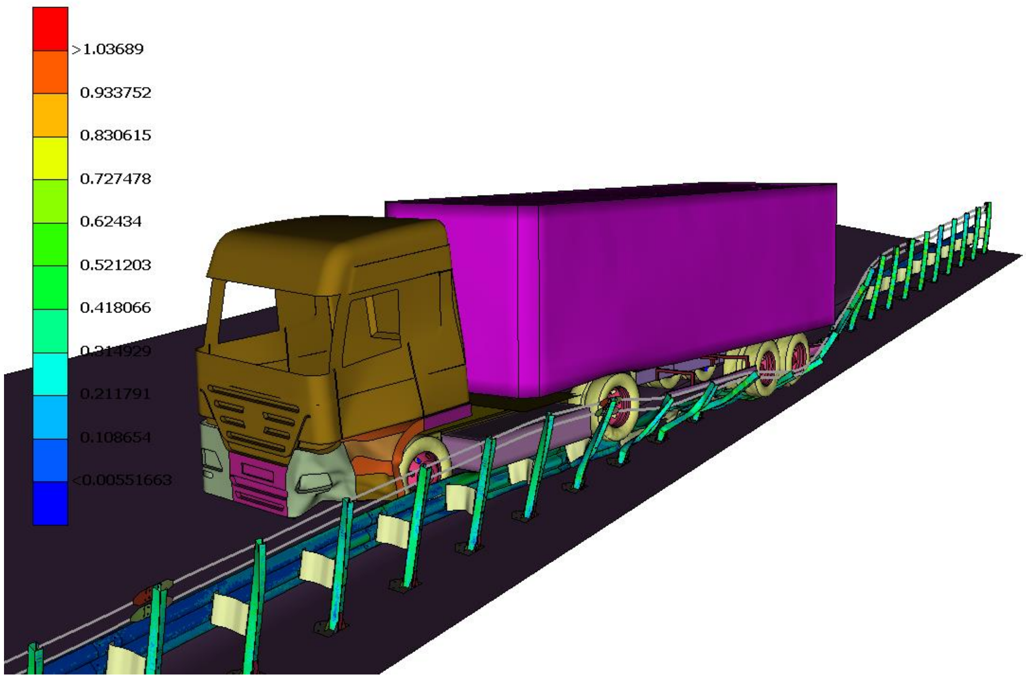

Fig.A24: Case study no.6, maximal deformation (m)

Energy balance of entire simulation is shown in Fig. A25. Yellow curve represents the non- physical energy (hourglass energy) and do not exceeds the recommended threshold of 4% of total energy.

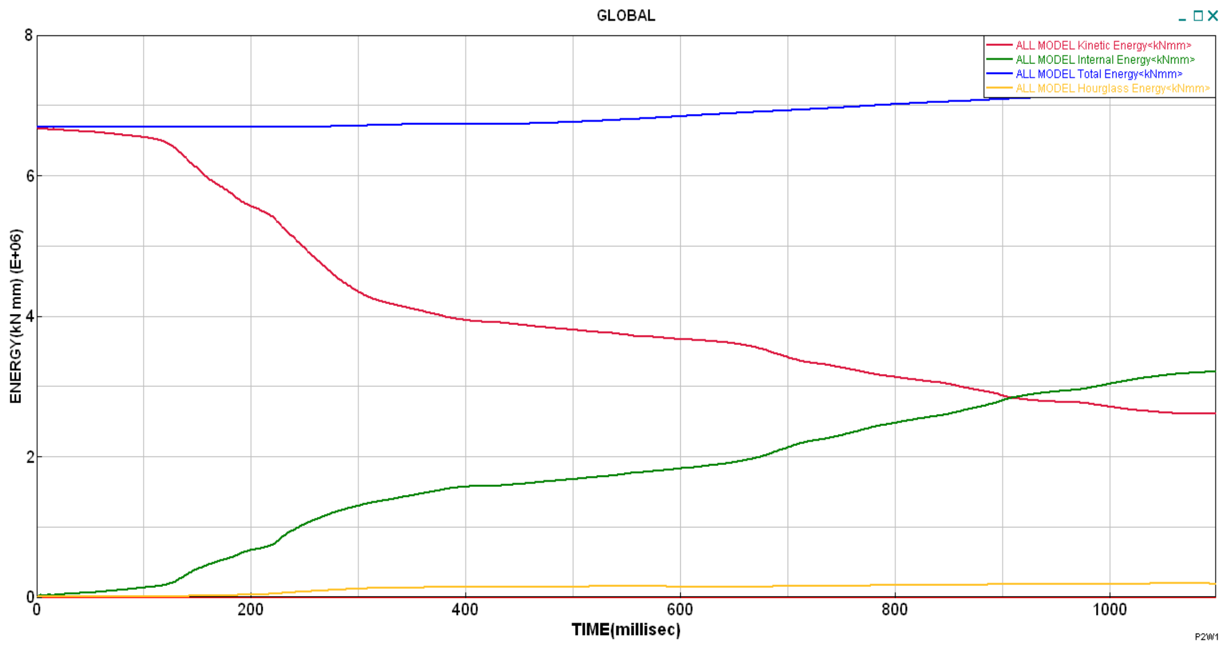

Fig.A25: Case study no.6, energy balance of the simulation

In Fig. A26 the contact force between the impact vehicle and road barrier system is shown. Graph represents the output from numerical simulation. Values cannot be compared with the real test due to the difficult measuring.

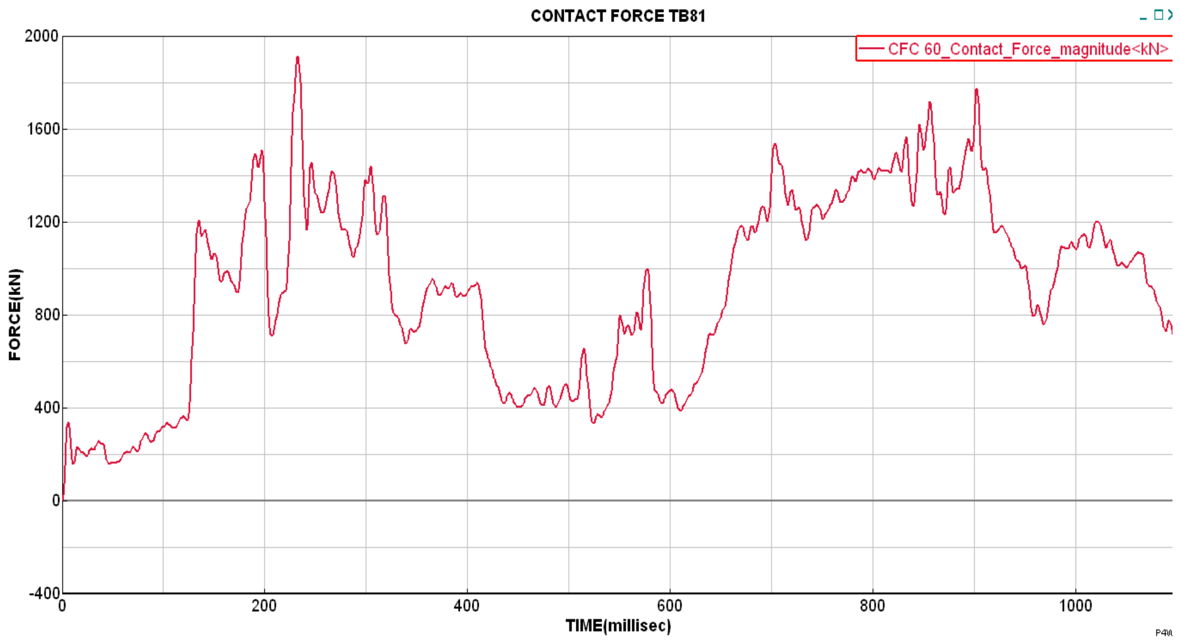

Fig.A26 : Case study no.6, vehicle – Road barrier contact force

The input conditions, geometry, and results of the numerical simulation with physical test are shown in the Tab.A5. It should be noted that this case study has limited information source from physical test (no technical report available). Therefore, some of the parameters cannot be compared.

Tab.A5: Case study no.6- Physical test / Simulation comparison

	Parameter	Physical Test	SIMULATION No.6	Difference
Initial conditions: Impact vehicle				
	Test Type acc. To EN 1317	**TB 81**	**TB81**	
	Vehicle type and model	IVECO MAGIRUS 440 - 1997/ TIRSAN XS - 2000	Truck with trailer standard model	
	Vehicle kerb mass [kg]	13090	N/A	--
	Total test mass [kg]	38340	38340	0%
	Dimension – length [mm]	16500	12700	-23%
	Dimension – width [mm]	2550	2550	0%
	Dimension – height [mm]	1480-platform	3500-trailer	--
	Wheelbase [mm]	12150	9970	-17,9%
	Wheel track – front [mm]	2040	2015	-1,2%
	Wheel track – rear [mm]	N/A	2171	--
	Nb. of axles	1S+4	1S+4	--
	Tyre Radius [mm]	510	502	-1,5%
Impact conditions:				
	Actual impact speed [km/h]	66,9	66,9	0%
	Actual impact speed [m/s]	18,58	18,58	0%
	Actual impact angle [deg]	20	20	0%
	Impact Energy [J]	774412	774412	0%
	Actual impact point location	0,36 m after transition elem 7/8	0,4 m before transition elem 5/6 (post no.13)	
	Test track condition	Dry	Frict = 0,6	--
Road barrier properties:				
	Material -overall	Steel	Steel	--
	Ground anchor	Bridge parapet	Bridge parapet	--
	Ground anchor depth [mm]	130	0	--
	System width [mm]	530	530	0%
	Post spacing [mm]	1500	1500	0%
	Post cross section	C120x80x30 L1480	C120x80x30	0%
	Post material (indication)	S355J2	S355JR	--
	Post Yield strength Re [Mpa]	N/A	471	--
	Post Ultimate strength Rm [Mpa]	N/A	551	--
	Post material Ductility A [%]	N/A	23	--
	Guardrail thickness [mm]	3	3	0%
	Guardrail material (indication)	S275JR	S355JR	--
	Guardrail Yield strength Re [Mpa]	N/A	471	--
	Guardrail Ultimate str. Rm [MPa]	N/A	551	--
	Guardrail material - ductility A [%]	N/A	23	--
	Guardrail height - centre [mm]	646		0%
Test Results:				
	Test Results	OK	OK	--
	Dynamic deflection [m]	0,9	0,97	+7,8%
	Normalised dyn. deflection [m]	0,9	1	+11%
	Working width [m]	2,0	2,1	
	Normalised working width [m]	2,0	2,0	

	Working width class	W6	W6	OK
	Vehicle inclination [m]	3,2	1,85	-42,2 %
	Vehicle inclination class	VI8	VI3	--
	Permanent deflection [m]	0,74	0,85	14,8 %
	Contact length [m]	20,65	17,9	-13,3 %
	Impact severity index	N/A	N/A	--
	Impact severity level	N/A	N/A	--

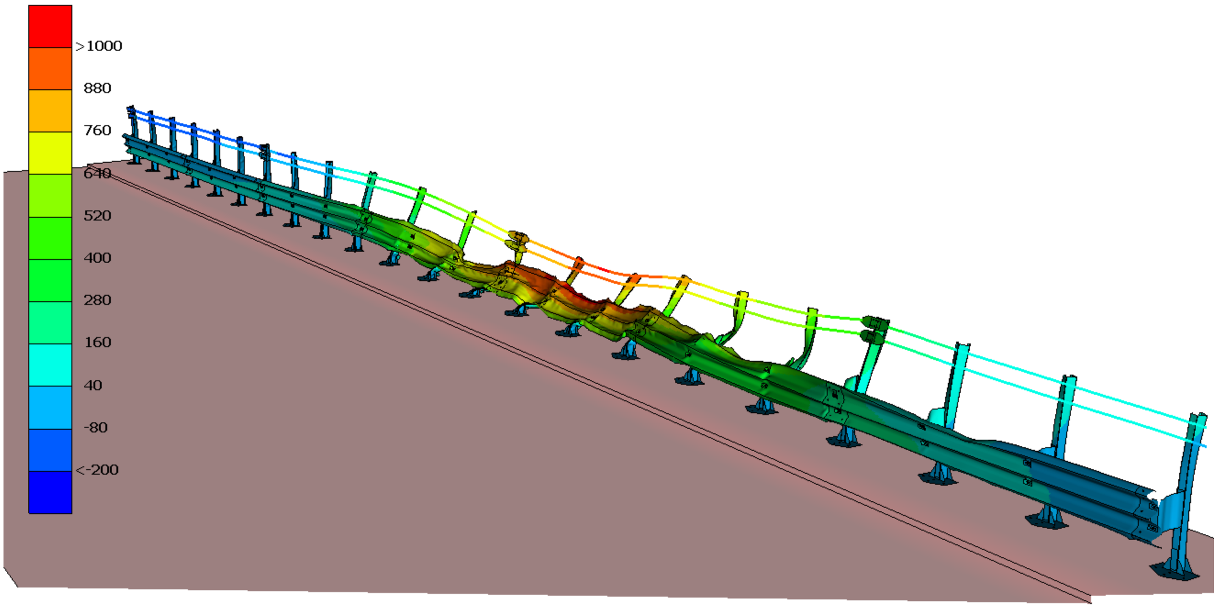

Fig. A27: Case study no.6, road barrier deformation after impact

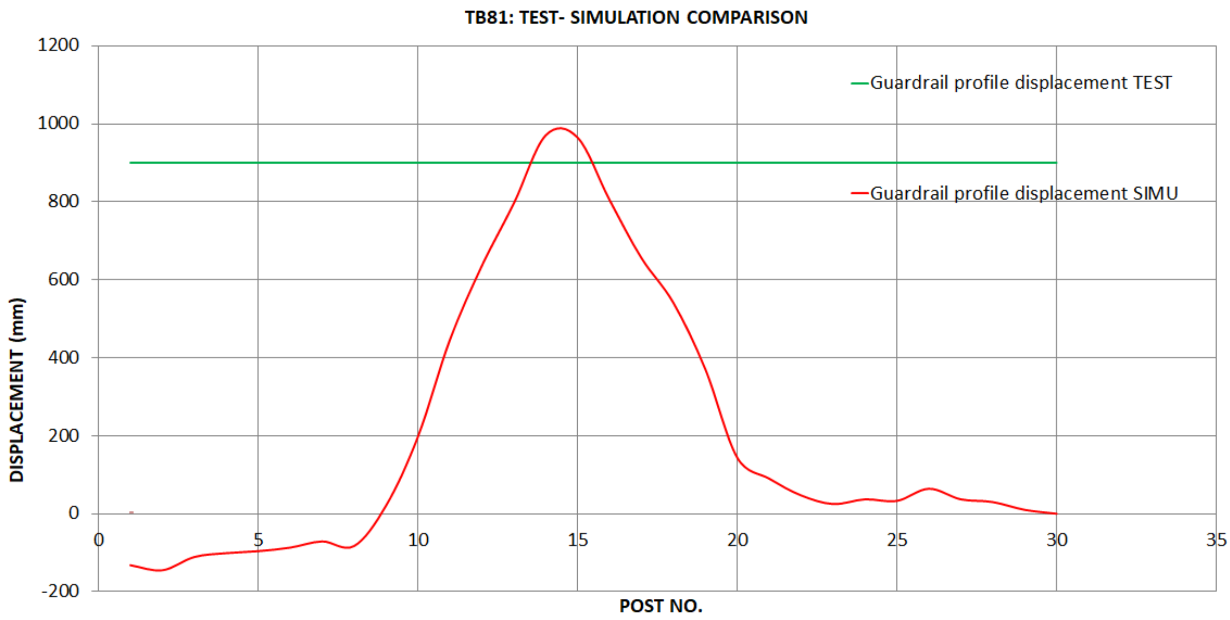

Fig. A28: Comparison of the test results in computer simulation and real crash test

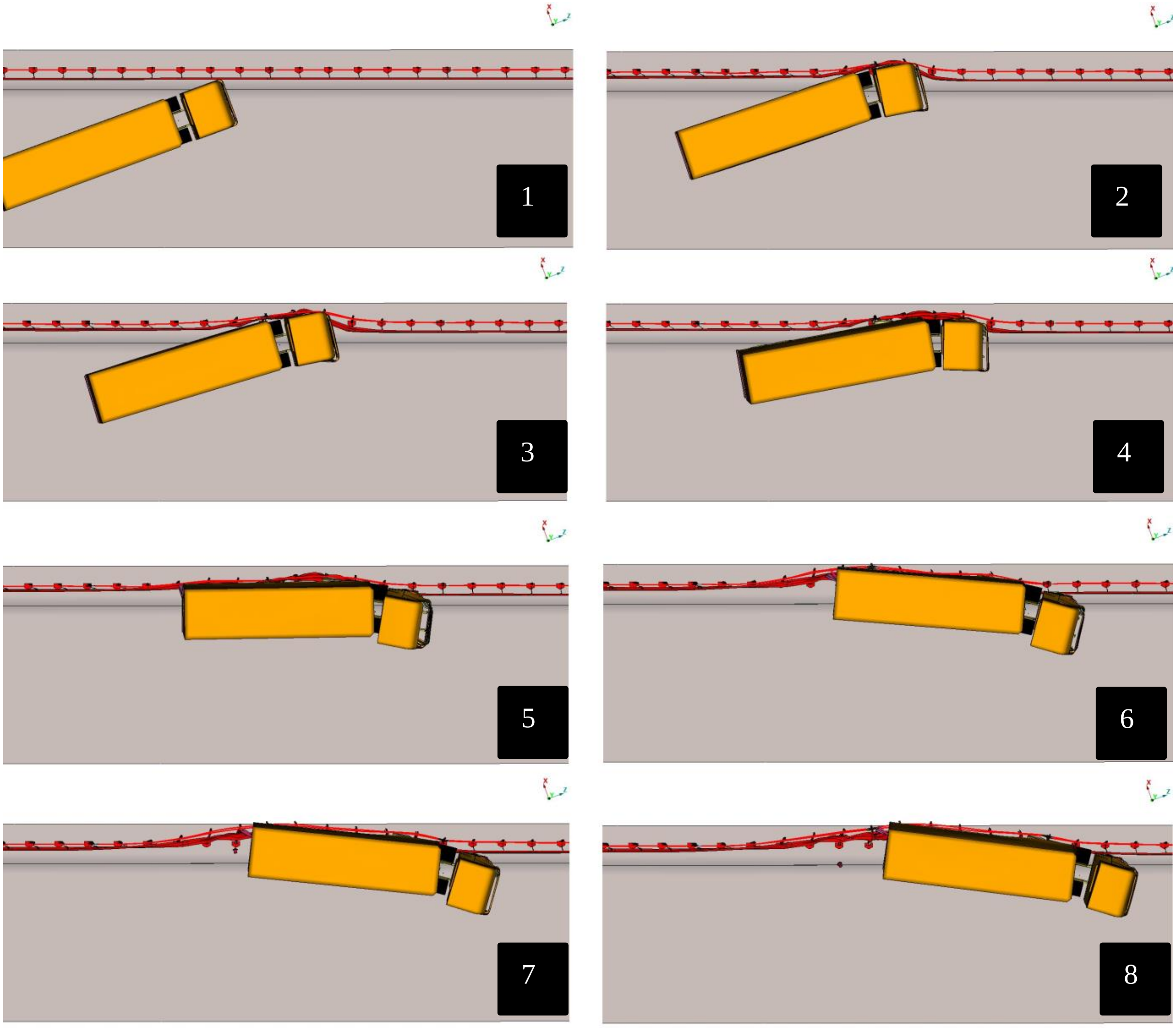

Fig.A29: Case study no.6, top view of the results

A1.6 Case study no.7

Numerical simulation of the simulation case study no.7 represents the physical test TB 81 with road barrier on the bridge parapet. This test has been conducted with truck and trailer as well. Road barrier is made of steel installed on the bridge parapet – see Fig. A30. The height of the parapet is 160mm from the road level and made of C25/C30 concrete.

A1.6.1 Crash test general information

Truck with mass 37020kg impact the road barrier with the actual impact speed 65,7 km/h and actual angle 20 deg. Initial conditions are within the tolerance defined in EN1317. Actual impact speed and actual angle combination is also within the tolerance envelope defined in EN 1317.

The posts are placed on the anchors, which are embedded in the foundation, and connected using 4 screws. The guardrail beams are connected to each second posts by collapsible elements. The guardrail beams are the B profile. The handrail is screwed on the top sides of the posts. Road barrier frontal face offset from the parapet is -40mm (in front of the parapet). The system is setup over distance of 60m and leading and trailing terminal section. System is shown in Fig. A30.

During and after the impact no more than one wheel of the vehicle passes over the rearmost part of the deformed system. Vehicle does not roll over during the test and no more than 5% of the cargo has been separated in the vehicle till the stop. Significant impact to the test results has a deformation capacity of the concrete in post anchorage area, therefore this feature must be reflected in virtual model as well.

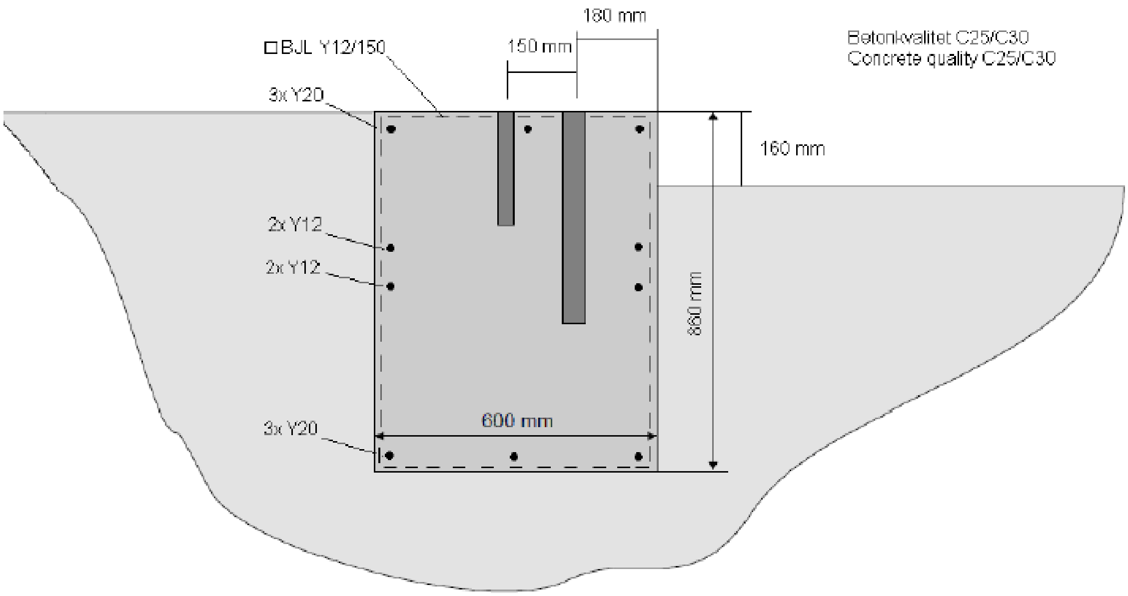

Fig.A30: Bridge parapet dimension used in case study no.7

A1.6.2 Simulation model global information

With regards to the real tests the truck impacts the road barrier 0,4m before transition element no.5 and 6. The initial conditions such an impact velocity, vehicle test mass and impact angle fully correspond with the real crash test values. Therefore, the impact energy 721,2 kJ is also the same. The simulation model was completed by the deformable material in post anchorage zone.

Simulation model consist of the following main parts:

- Impact vehicle:

- Fully deformed truck and trailer with the kinematic suspension and revolving wheels. Trailer is connected to the truck via kinematic joint.
- Defined pressure inside the tyres.

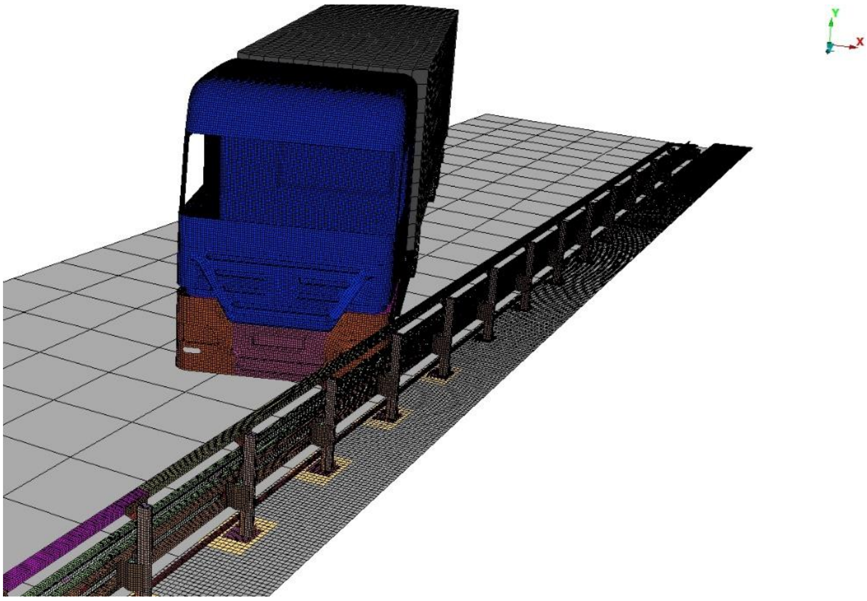

Fig.A30: FE model of the crash test in case study no.7

- Road
  - Rigid body definition.
  - Bridge parapet 160mm.
  - Deformable area in post anchorage location – represents the concrete deformation capacity.
- Road barrier model:
  - Total length of 60 m.
  - Bolts detailed model – in crash area only.
  - Total of 41 posts fixed on the bridge parapet.

A1.6.3 Case study no.7 verification

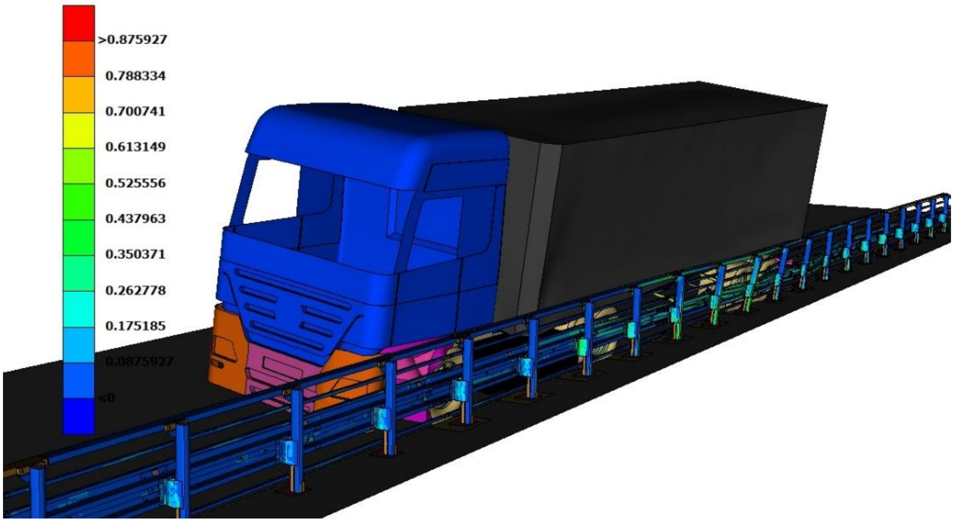

Fig.A31: Case study no.7, maximal deformation

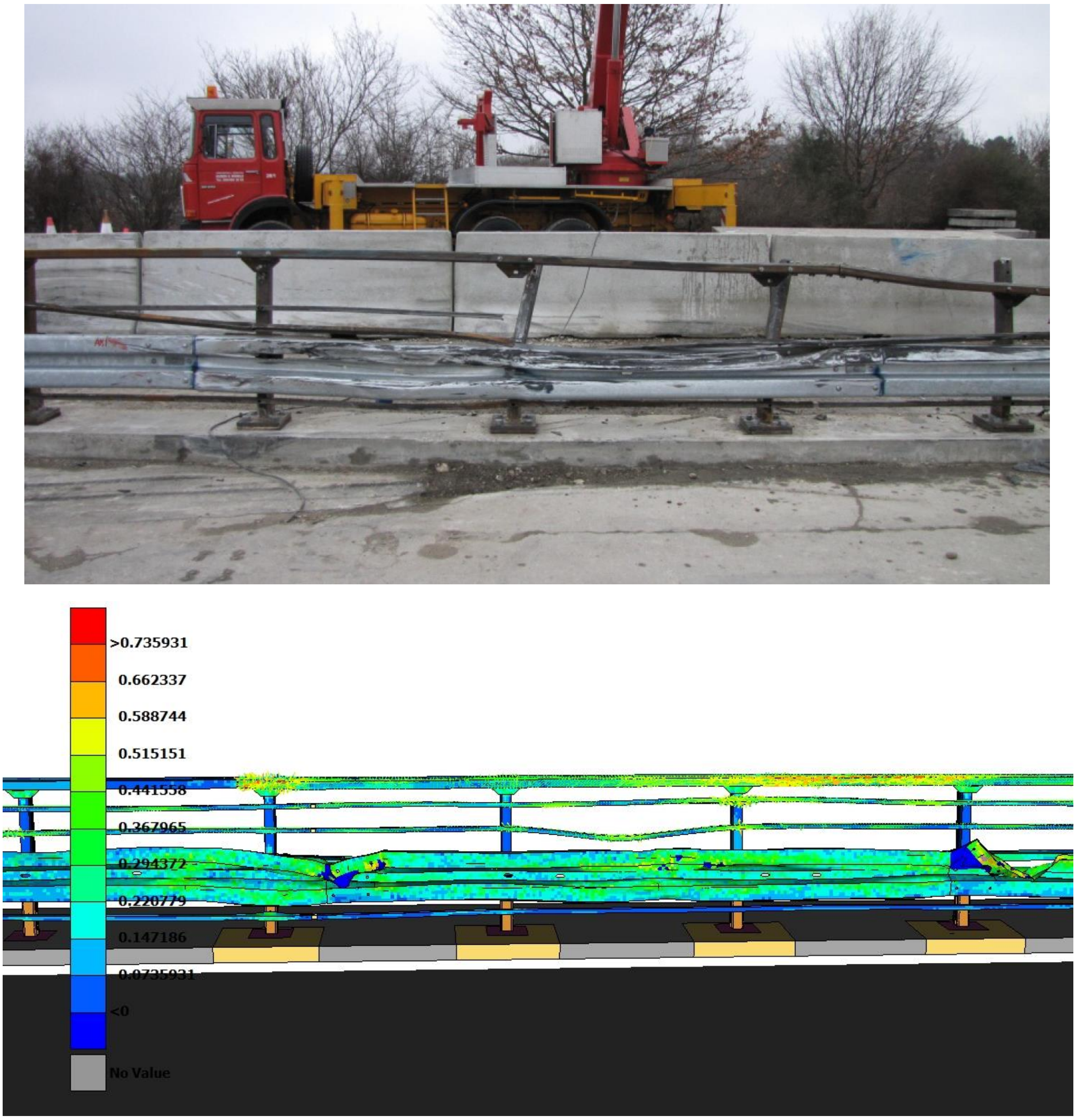

Fig.A31: Case study no.7, barrier deformation comparison (simulation and real crash test)

Energy balance of entire simulation is shown in Fig. A33. Yellow curve represents the non- physical energy (hourglass energy) and do not exceeds the recommended threshold of 4% of total energy.

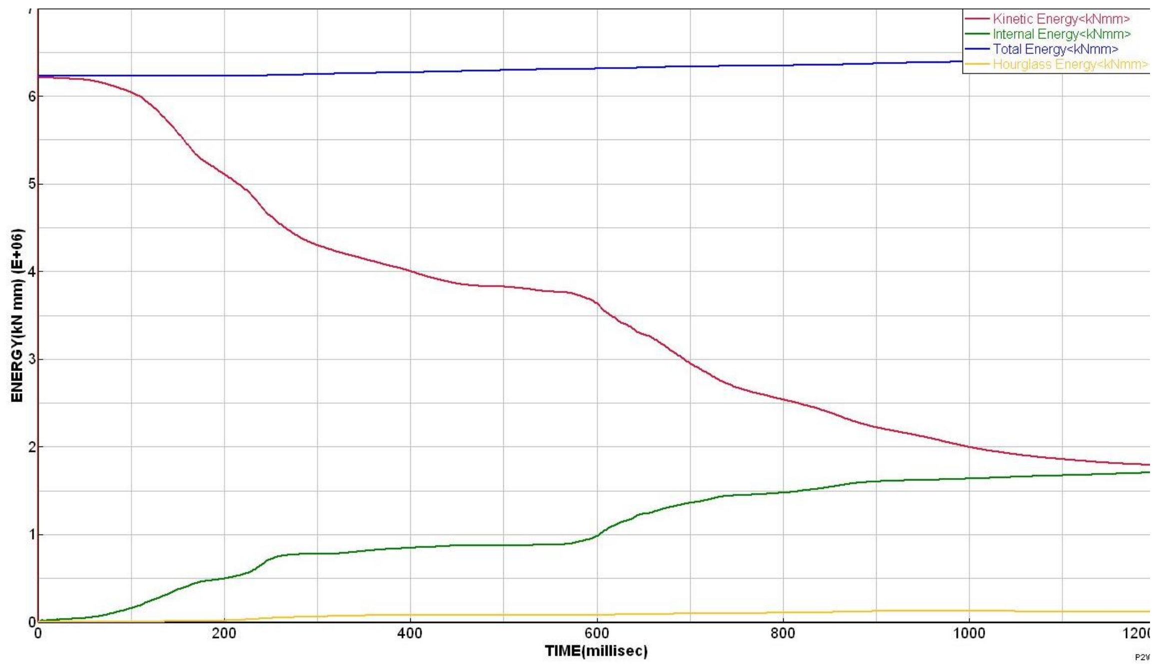

Fig.A33: Case study no.7, energy balance of the simulation

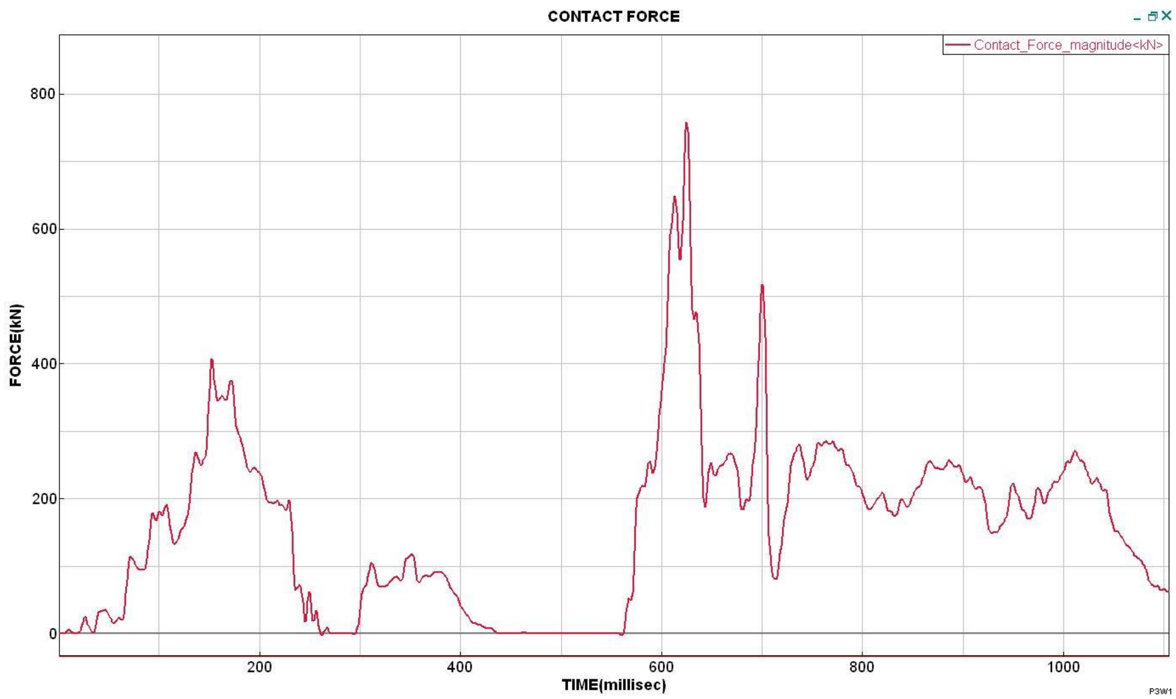

Fig.A34: Case study no.7, Vehicle – Road barrier contact force

The results of the numerical simulation compared to the physical test results are shown in the Tab.A6. Initial conditions are also compared in the table.

Tab.A6: Case study no.7- Physical test / Simulation comparison

	Parameter	Physical Test	SIMULATION No.7	Difference
Initial conditions: Impact vehicle				
	Test Type acc. To EN 1317	**TB 81**	**TB81**	
	Vehicle type and model	MAN 19.414 FLT / Kogel SF HB 24	Truck standard	
	Vehicle kerb mass [kg]	12020	N/A	N/A

	Total test mass [kg]	37020	37020	0%
	Dimension – length [mm]	16500	12700	-23%
	Dimension – width [mm]	2550	2550	0%
	Dimension – height [mm]	1250-platform	3500-trailer	--
	Wheelbase [mm]	12000	9970	-16,9%
	Wheel track – front [mm]	2050	2015	-1,7%
	Wheel track – rear [mm]	N/A	2171	--
	Nb. of axles	1S+4	1S+4	--
	Tyre Radius [mm]	550	502	-8,7%
Impact conditions:				
	Actual impact speed [km/h]	65,7	65,7	0%
	Actual impact speed [m/s]	21,9	21,9	0%
	Actual impact angle [deg]	20	20	0%
	Impact Energy [J]	721165	721165	0%
	Actual impact point location	0,4 m before transition elem 5/6 (post no.13)	0,4 m before transition elem 5/6 (post no.13)	
	Test track condition	Dry	Frict = 0,4	--
Road barrier properties:				
	Material -overall	Steel	Steel	--
	Ground anchor	Bridge parapet	Bridge parapet	--
	Ground anchor depth [mm]	100	0	--
	System width [mm]	440	440	0%
	Post spacing [mm]	1500	1500	0%
	Post cross section	120x80x10+ Full profile in anchorage	120x80x10+ Full profile in anchorage	--
	Post material (indication)	S355J2	S355J2H	--
	Post Yield strength Re [Mpa]	N/A	443	--
	Post Ultimate strength Rm [Mpa]	N/A		--
	Post material Ductility A [%]	N/A	27	--
	Guardrail thickness [mm]	3,0	3,0	0%
	Guardrail material (indication)	S235JR	S235JR	--
	Guardrail Yield strength Re [Mpa]	N/A	281	--
	Guardrail Ultimate str. Rm [MPa]	N/A		--
	Guardrail material - ductility A [%]	N/A	26	--
	Guardrail height - centre [mm]	430 + parapet	430	0%
Test Results:				
	Test Results	OK	OK	--
	Dynamic deflection [m]	0,3	0,317	+5,7%
	Normalised dyn. deflection [m]	0,3	0,3	0%
	Working width [m]	0,9	0,9	0%
	Normalised working width [m]	0,9	0,9	0%
	Working width class	W3	W3	OK
	Vehicle inclination [m]	1,2	1,35	+12,5%
	Vehicle inclination class	VI4	VI4	--
	Permanent deflection [m]	0,22	0,23	+4,5%
	Contact length [m]	40,4		
	Impact severity index	N/A	N/A	--
	Impact severity level	N/A	N/A	--

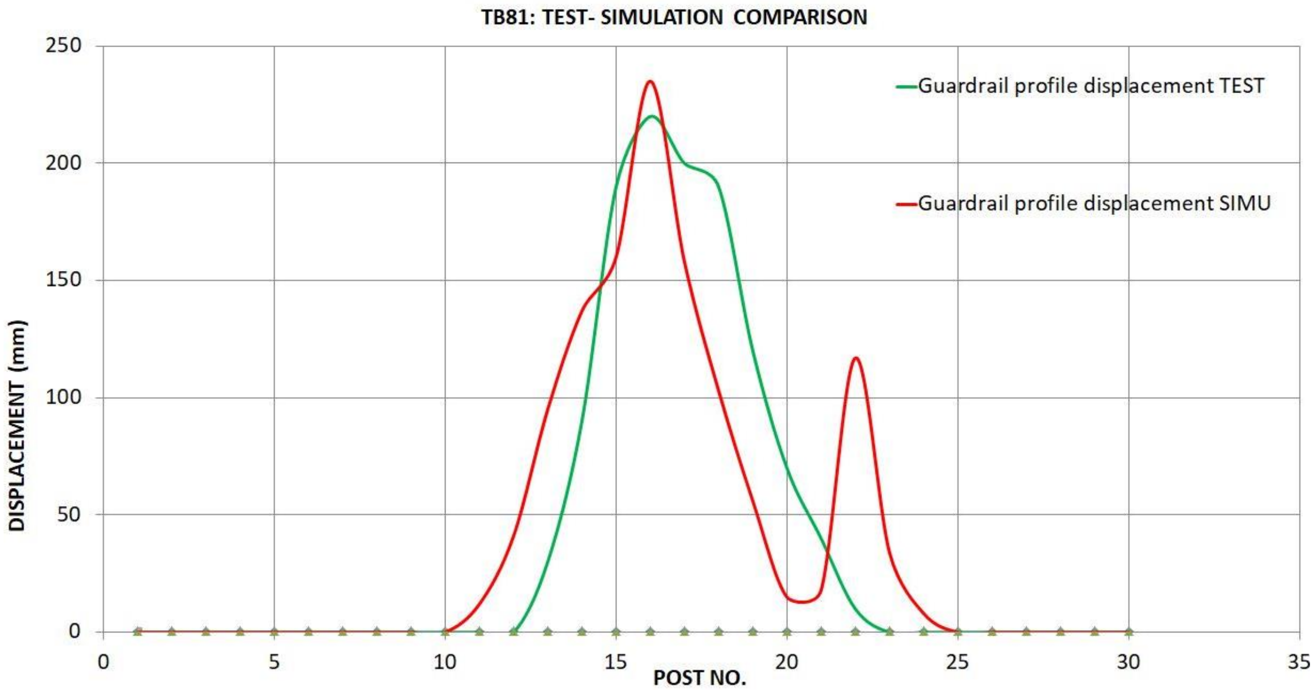

Fig. A35: Comparison of the post deformation (Test –Simulation)

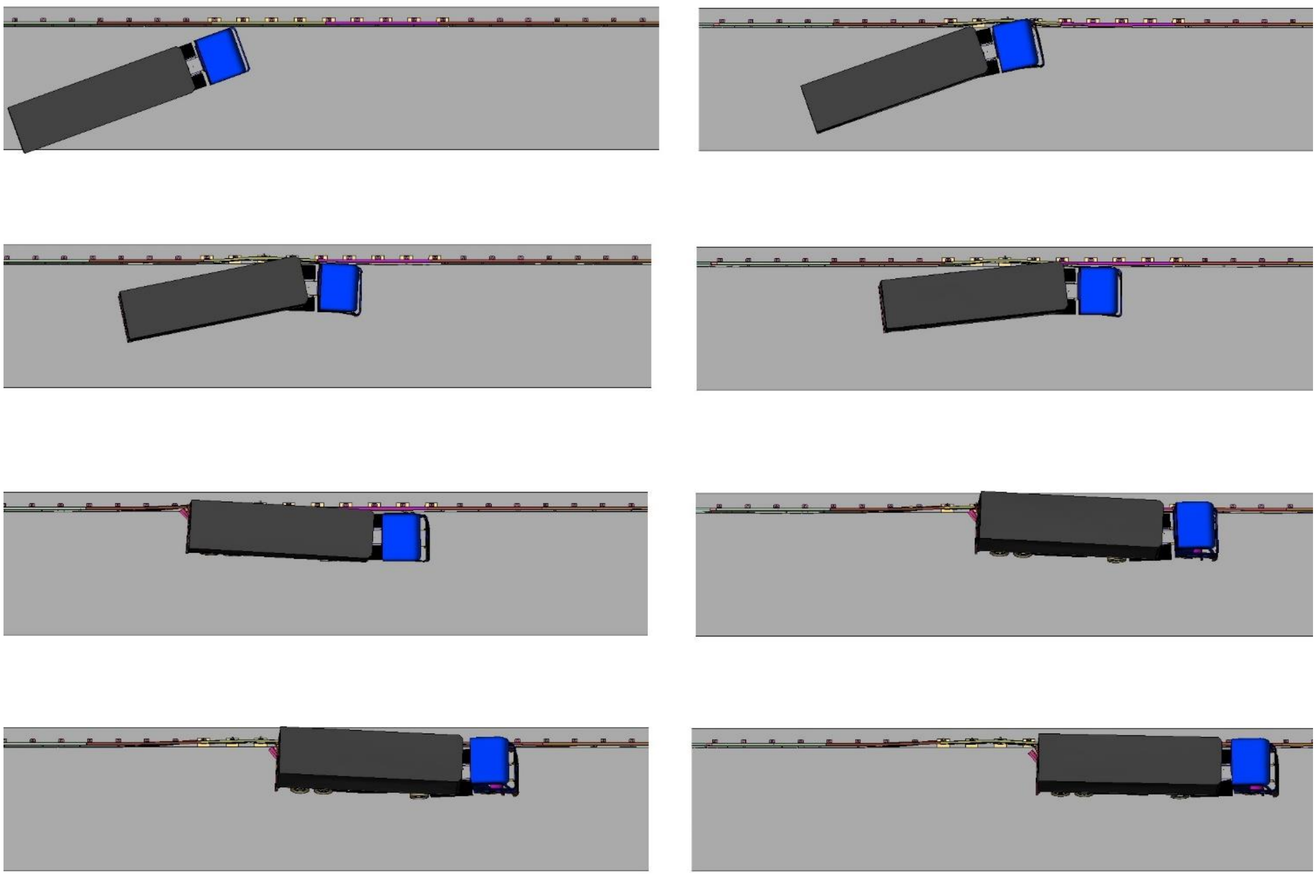

Fig.A36: Case study no.7, top view of the results

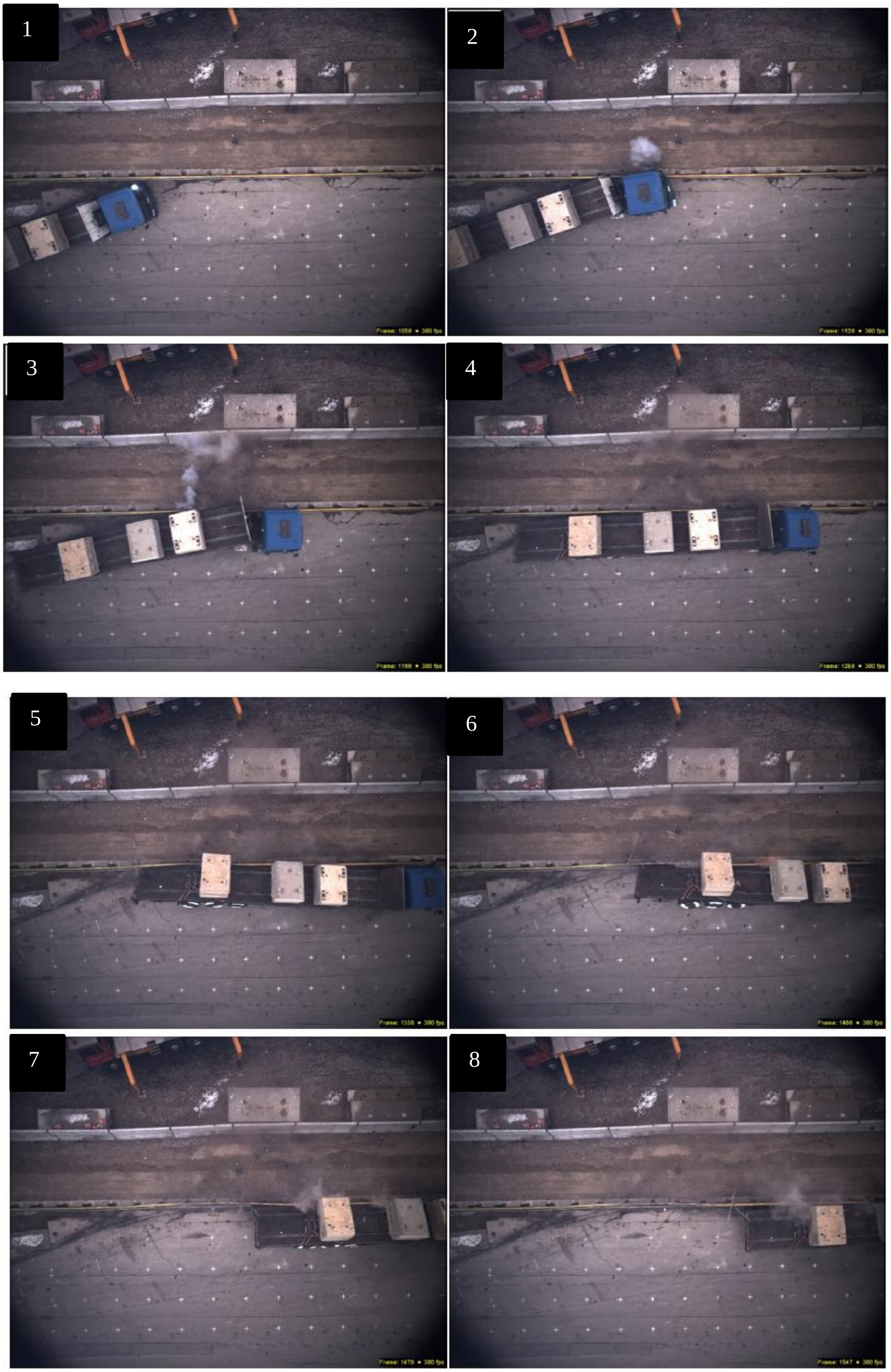

Fig.A37: Case study no.7, top view of the real crash test results

A1.7 Case study no.8

Last simulation no.8 represents the virtual picture of crash test TB 11. Tests TB11 were involved in the validation process even if the thesis is mainly focused on heavy vehicle impacts. This test has been conducted with small passenger car (Peugeot 106) and road barrier made of steel rammed into the ground. Road barrier test sample is typical product used along central Europe incl. Czech Republic.

A1.7.1 Crash test general information

Vehicle hits the road barrier with the actual impact speed 101,57 km/h and actual angle 20,3 deg. Initial conditions are within the tolerance defined in EN1317. Actual impact speed and actual angle combination is also within the tolerance envelope defined in EN 1317.

During and after the impact no more than one wheel of the vehicle passes over the rearmost part of the deformed system. Vehicle does not roll over during the test. Information package related to the road barrier and crash test has been completed by Technical Report from the physical test. Information from the report has been utilized to validate the simulation approach in detail.

A1.7.2 Simulation model global information

Vehicle hits the road barrier 0,6m left from the post no.20. The initial conditions given by impact velocity; vehicle test mass and impact angle fully correspond with the real crash test values. Therefore, the impact energy 345,20 kJ is the same.

Simulation model consist of the following main parts:

- Impact vehicle:
    - Fully deformed vehicle with the kinematic suspension and revolving wheels.
    - Defined pressure inside the tyres.

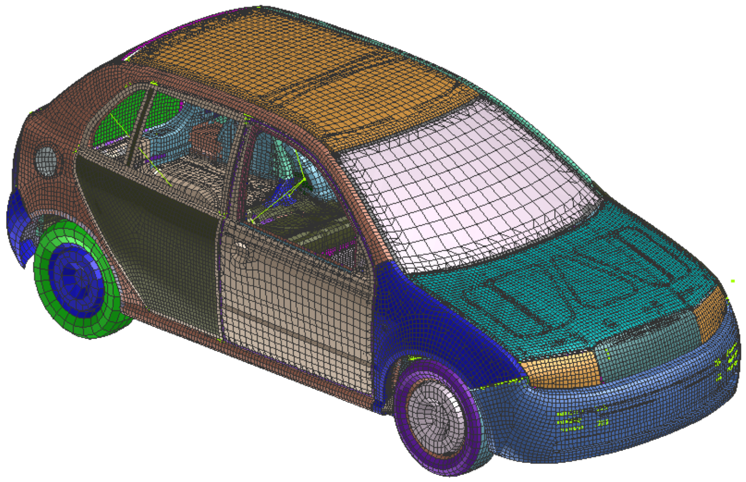

Fig.A38: FE model of the passenger car used in case study no.8

- Road barrier model:
    - Total length of 105 m, incl. the leading and trailing parts.
    - Bolts detailed model – in crash area only.
    - Total of 96 posts fixed just in the road level.

Entire model of the crash test consists of 703 300 elements. Nominal mesh size is defined with respect to the behaviour and expected deformation:

Road barrier guard rail and posts – element length 12mm

Vehicle impact area: - element length 12 mm

Vehicle non-impact area - element length 50 mm

Road - element length 1000mm

Overall view of the numerical model is shown in the Fig.A39.

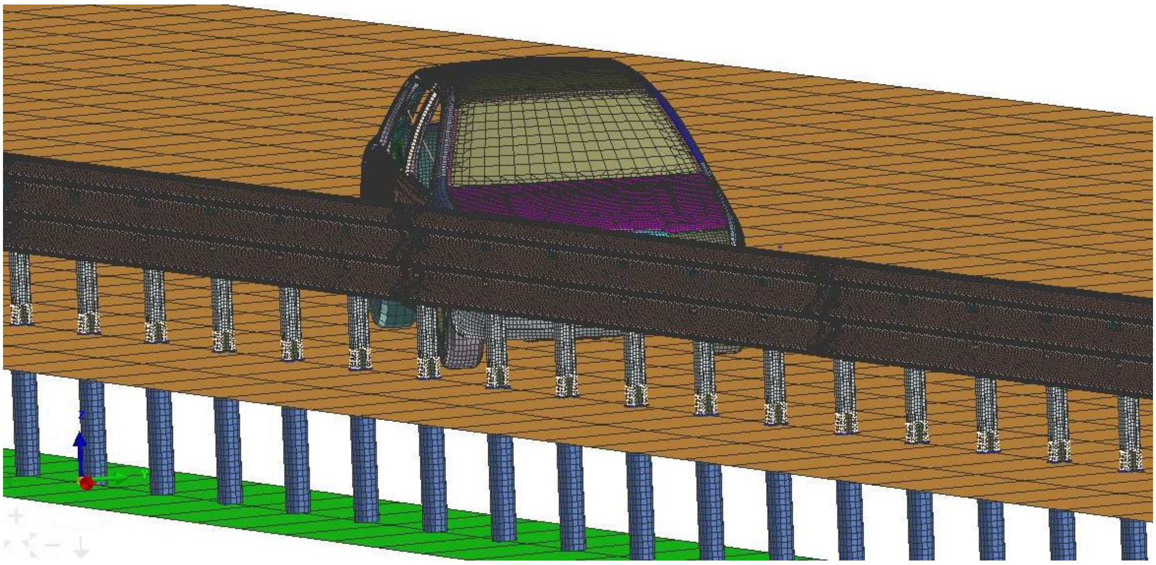

Fig.A39: Overall view of the numerical model from simulation case study no.8

A1.7.3 Case study no.8 verification

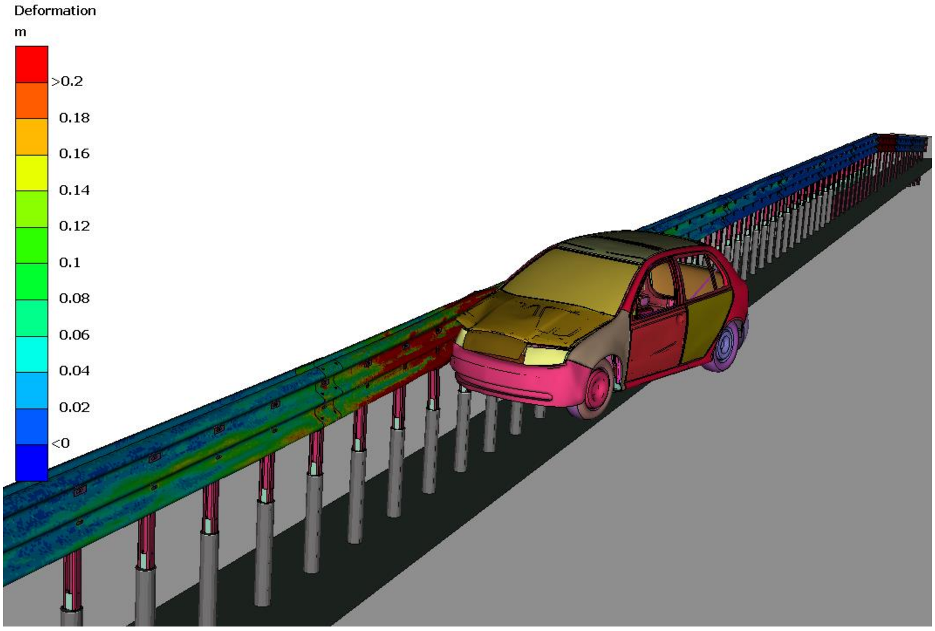

Fig.A40: Case study no.8, initial contact with road barrier

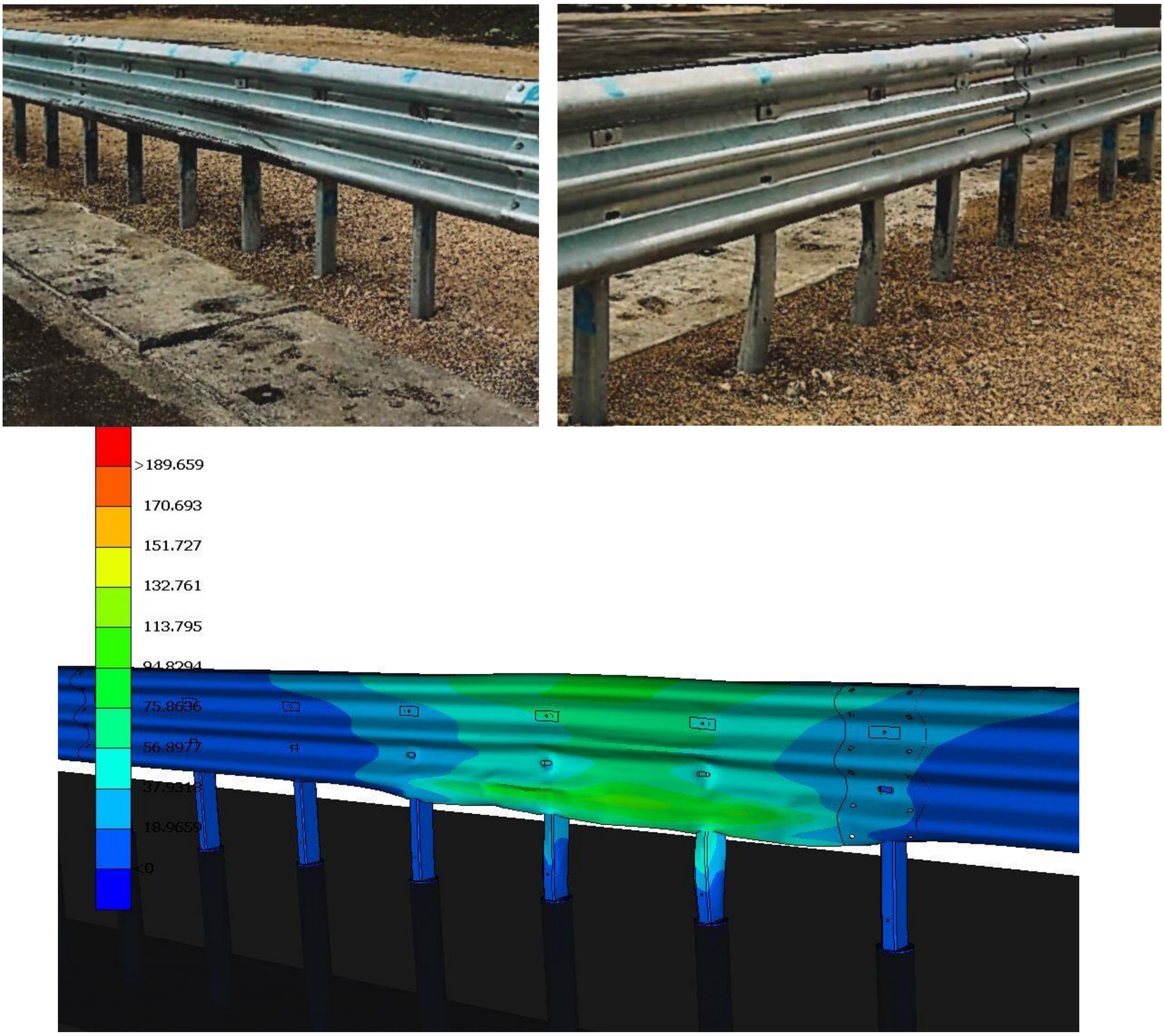

Fig.A41: Case study no.8, road barrier permanent deflection –comparison real test - simulation

The evidence of the simulation results validity is displayed in graph Fig.A42 – A44. Energy balance of entire simulation is shown in Fig. A42. It is obvious that calculation progress has no failure or unclear phenomena. Yellow curve represents the non- physical energy (hourglass energy) and do not exceeds the recommended threshold of 4% of total energy. Smooth energy transformation among kinetic energy (red curve) and internal energy of the system (green curve) is shown and appreciated.

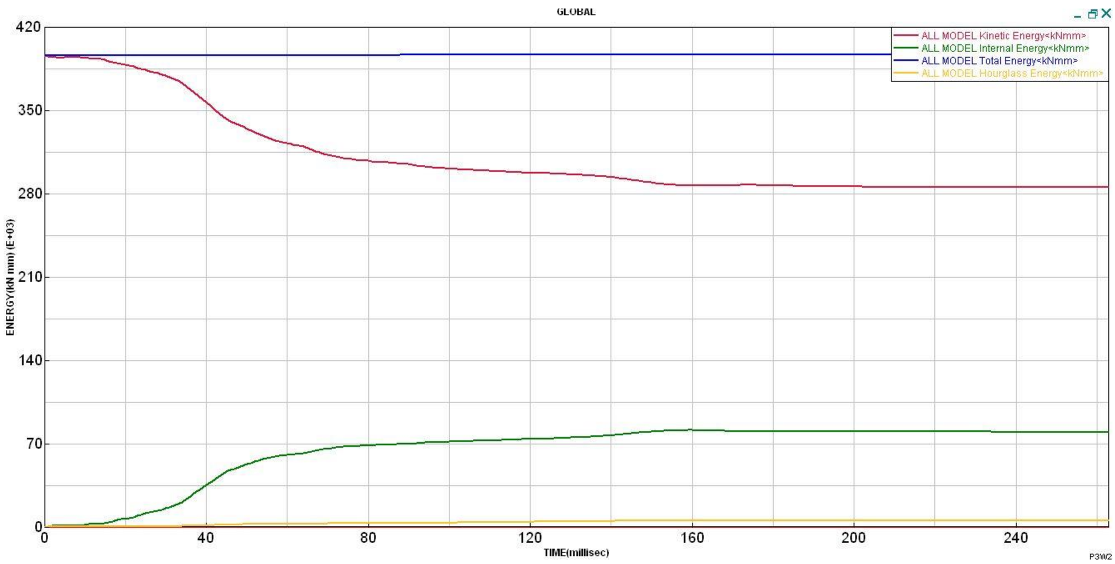

Fig.A42: Case study no.8, energy balance of the simulation

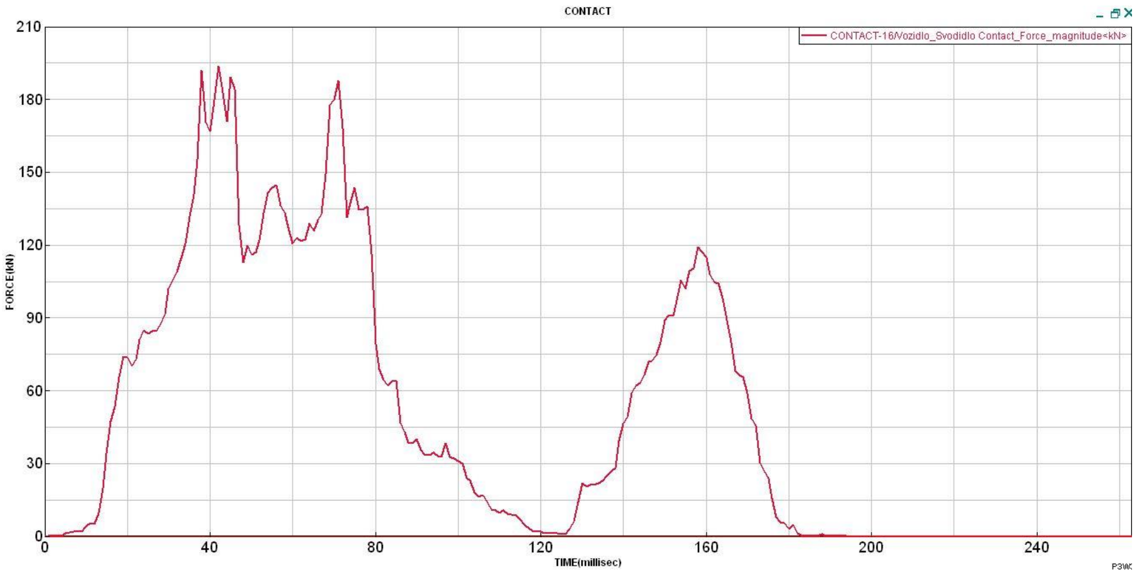

Fig.A43: Case study no.8, vehicle / road barrier contact force

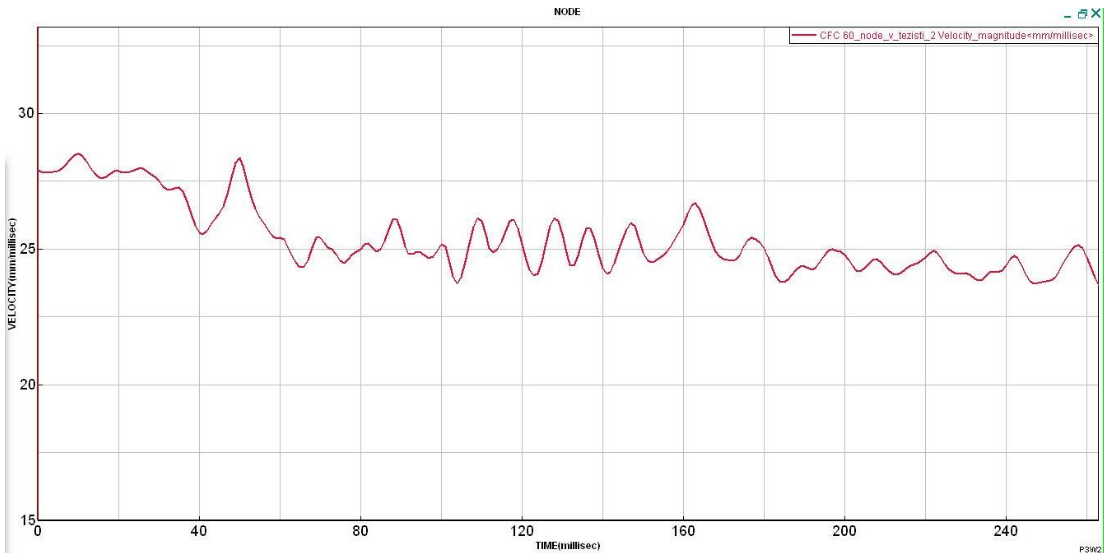

Fig.A43: Case study no.8, vehicle velocity time history

Unfortunately, the vehicle velocity time history from crash test is not available.

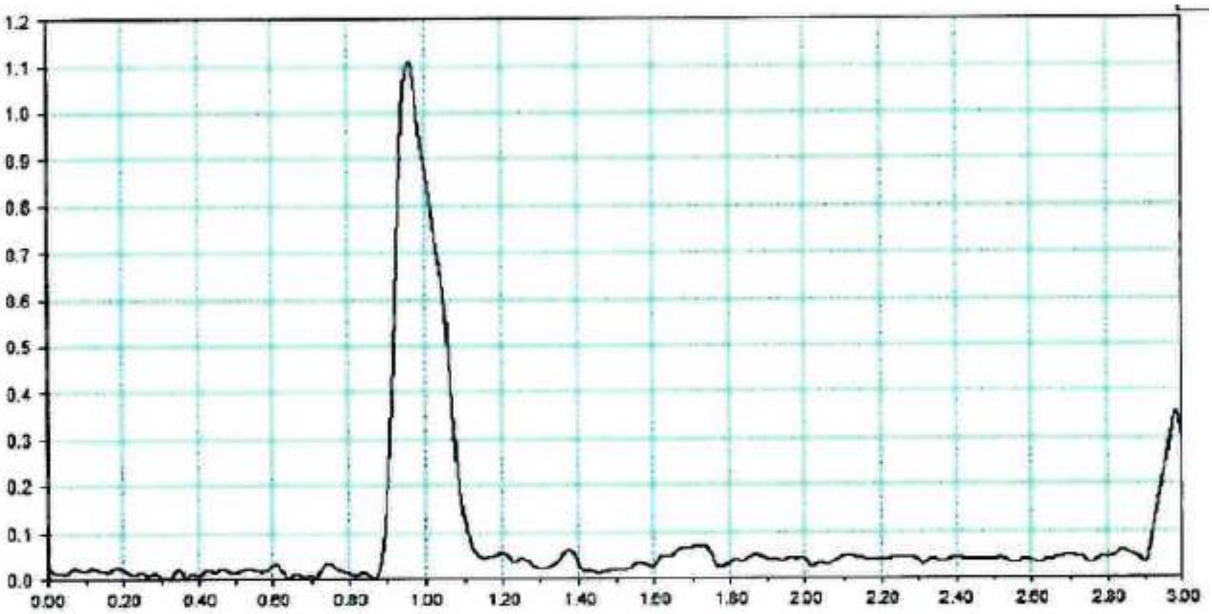

Fig.A44: Real test: Acceleration severity index ASI time history.

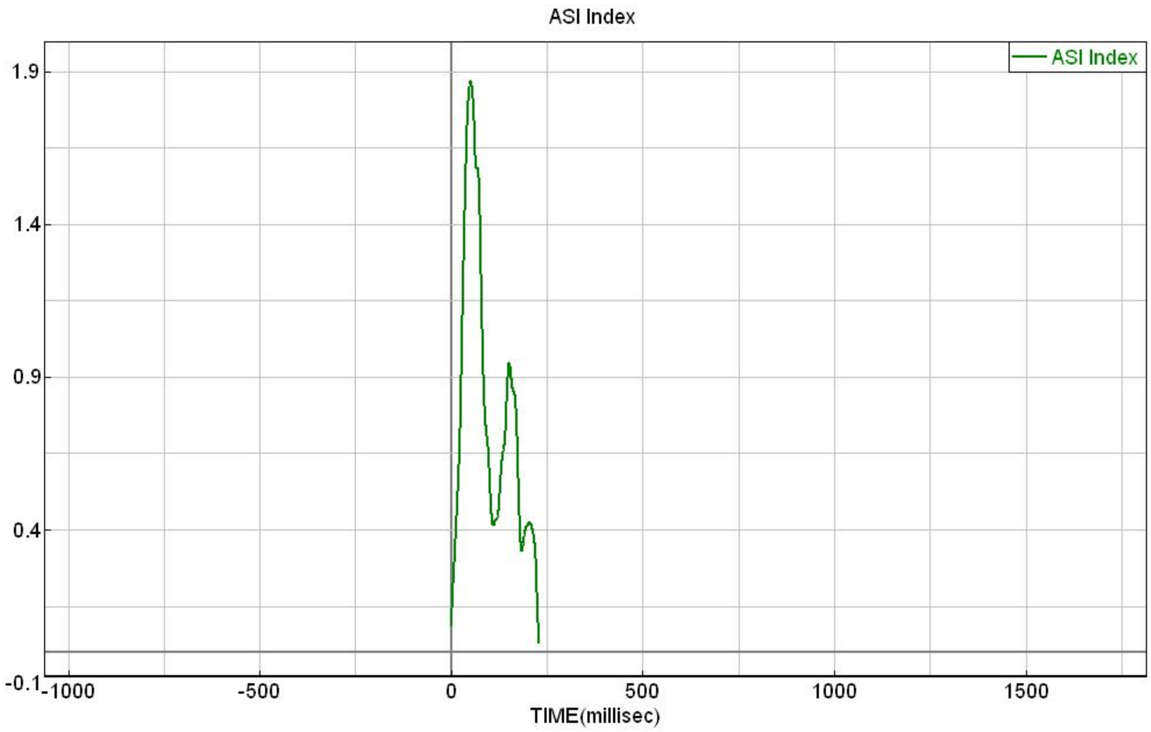

Fig.A45: Case study no.8, acceleration severity index ASI time history.

The results of the numerical simulation compared to the physical test results are shown in the Tab.A7.

Tab.A7: Case study no.8- Physical test / Simulation comparison

	Parameter	Physical Test	SIMULATION No.8	Difference
Initial conditions: Impact vehicle				
	Test Type acc. To EN 1317	**TB 11**	**TB11**	
	Vehicle type and model	Fiat UNO , 1989	Skoda Fabia I gen.	--
	Vehicle kerb mass [kg]	736,5	N/A	N/A
	Total test mass [kg]	866	866	0
	Dimension – length [mm]	3600	3873	+7,5%
	Dimension – width [mm]	1580	1595	+1%
	Dimension – height [mm]	1410	1410	0
	Wheelbase [mm]	2300	2438	+6%
	Wheel track – front [mm]	1330	1399	+5,2%
	Wheel track – rear [mm]	1300	1345	+3,4%
	Nb. of axles	1S+1	1S+1	--
	Tyre Radius [mm]	N/A	518	--
Impact conditions:				
	Actual impact speed [km/h]	101,57	101,5	0%
	Actual impact speed [m/s]	27,92	28,21	0%
	Actual impact angle [deg]	20,3	20,3	0%
	Impact Energy [J]	40 631	40 631	0%
	Actual impact point location	33m left from post1	33m left from post1	--
	Test track condition	Dry	Frict = 0,4	--
Road barrier properties:				
	Material -overall	Steel	Steel	--
	Ground anchor	Ground	Posts fix in road	--
	Ground anchor depth [mm]	805	880	+9,3%
	System width [mm]	270	270	0%
	Post spacing [mm]	750	750	0%
	Post cross section	C100x60x25	C100x60x25	--
	Post material (indication)	S355JR	S355JR	--
	Post Yield strength Re [Mpa]	409	408	0%
	Post Ultimate strength Rm [Mpa]	506	506	0%
	Post material Ductility A [%]	24	24	0%
	Guardrail thickness [mm]	2,3	2,3	0%
	Guardrail material (indication)	S355JR	S355JR	---
	Guardrail Yield strength Re [Mpa]	471	471	0%
	Guardrail Ultimate str. Rm [MPa]	551	551	0%
	Guardrail material - ductility A [%]	23	23	0%
	Top Guardrail height - centre [mm]	647,5	650	0%
Test Results:				
	Test Results	OK	OK	--
	Dynamic deflection [m]	0,1	0,1	0%
	Normalised dyn. deflection [m]	0,1	0,1	OK
	Working width / class [m]	0,3	0,3	0%
	Normalised working width [m]	0,3	0,3	0%
	Working width class	W1	W1	OK
	Permanent deflection [m]	0,1	0,1	0%
	Contact length [m]	5,0	4,1	-18%
	Impact severity index / level	1,1 /B	1,85/C	+68%

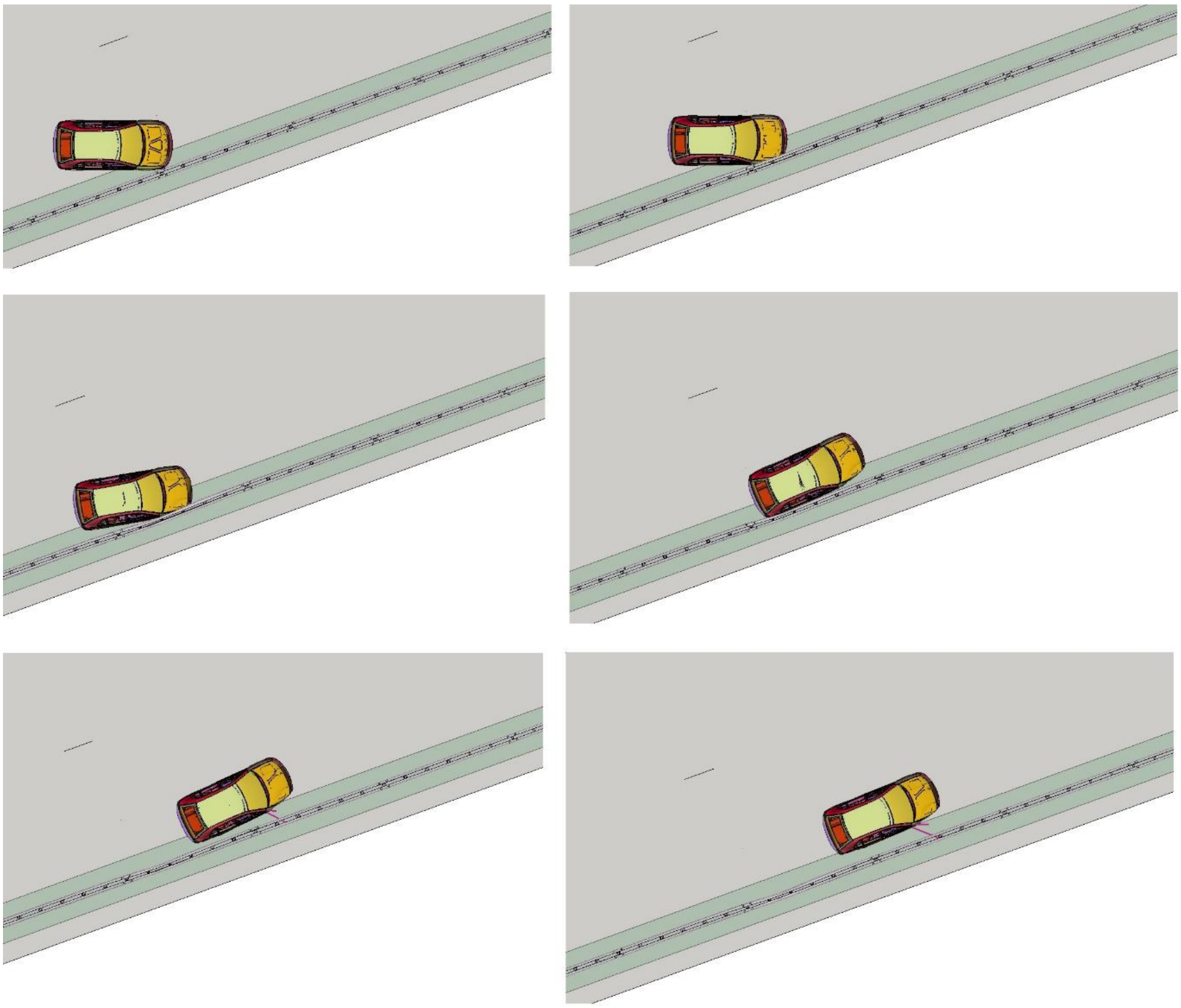

Fig.A46: Case study no.8, top view of the results - simulation

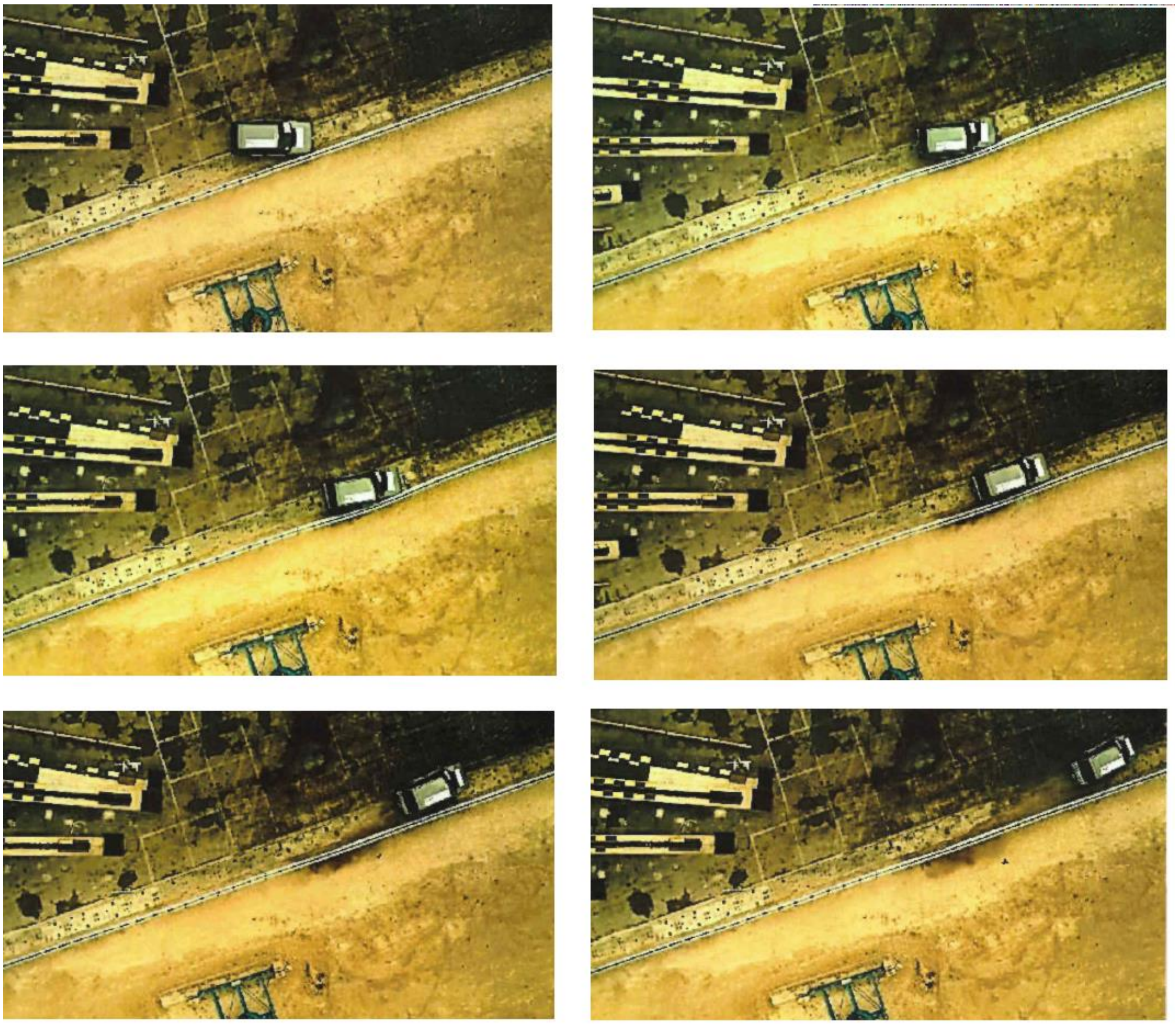

Fig.A47: Case study no.8, top view of the results- crash test

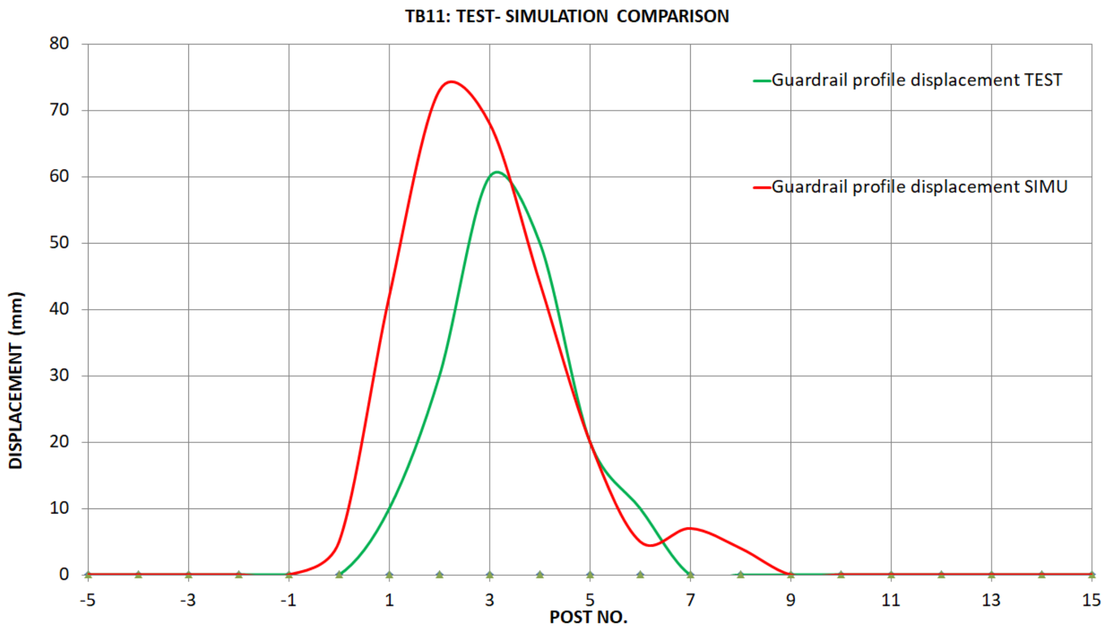

Fig. A48: Comparison of the post deformation (Test –Simulation)

A1.8. Results summary

The outputs of total 8 case studies are summarized in Tab. A8. The test identification incl. the type of the impacting vehicle and impact energy is also displayed. The difference in percentage means how different is the simulation result from physical test result. Positive value means that simulation gets the higher values, therefore is conservative. For acceptance criteria OK means that simulation outputs correspond with the physical test behaviour. The results were compared with regards to the test criteria:

- Acceptance criteria:
    - Point 1: Road barrier contained the test vehicle Y/N
    - Point 2: Major parts (longitudinal elements) fractured or detached Y/N
    - Point 3: Detached parts over the mass 2kg Y/N
    - Point 4: Pieces of restraint system in cabin Y/N
    - Point 5: Vehicle rolls over within the test Y/N
    - Point 6: During the test no more than one-wheel passes over the rearmost part of the deformed system Y/N
- Maximal dynamic deflection *D* in test
- Maximal residual deformation after the test
- Vehicle – road barrier contact length
- Vehicle cockpit deformation index and overall vehicle deformation

Tab. A8: Simulation case studies – results summary

Case study No.		1	2	3	4	5	6	7	8
Test Description		TB51	TB11	TB51	TB51	TB51	TB81	TB81	TB11
Impact vehicle		Bus	Small car	Bus	Bus	Bus	Truck + trailer	Truck + trailer	Small car
Impact energy [kJ]		316,2	42,1	292,8	285,5	294,8	774,4	721,2	40,6
Acceptance criteria	Point 1	OK	OK	OK	OK	OK	OK	OK	OK
	Point 2	OK	OK	OK	OK	OK	OK	OK	OK
	Point 3	OK	OK	OK	OK	OK	OK	OK	OK
	Point 4	OK	OK	OK	OK	OK	OK	OK	OK
	Point 5	OK	OK	OK	OK	OK	OK	OK	OK
	Point 6	OK	OK	OK	OK	OK	OK	OK	OK
Maximal dynamic deflection		-3.5%	+4.7%	N/A	-7,1%	+10%	7,8%	-1,6%	0%
Maximal residual deformation		+2.9%	+3.8%	N/A	-20%	+13,5%	14,9%	+13,6%	0%
Contact length		-11.8%	-27.2%	N/A	-11%	-20,8%	-13,3%	+22,7%	-18%
Vehicle cockpit deformation index		OK	OK	N/A	N/A	N/A	N/A	N/A	OK
Impact severity index ASI		N/A	+94%	N/A	N/A	N/A	N/A	N/A	+68%